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# A Bridge Rehabilitation Strategy Based on the Analysis of a Dataset of Bridge Inspections in Co. Cork

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# Declaration

A thesis submitted to Cork Institute of Technology in fulfilment of the degree MEng

I affirm that this thesis is entirely my own work except where otherwise credited and that this thesis has not been submitted for an award at any other institution.

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## Abstract

**A Bridge Rehabilitation Strategy based on the Analysis of a Dataset of Bridge Inspections in Co. Cork.**

Ageing highway structures present a challenge throughout the developed world. The introduction of bridge management systems (BMS) allows bridge owners to assess the condition of their bridge stock and formulate bridge rehabilitation strategies under the constraints of limited budgets and resources. This research presents a decision-support system for bridge owners in the selection of the best strategy for bridge rehabilitation on a highway network. The basis of the research is an available dataset of 1,367 bridge inspection records for County Cork that has been prepared to the Eirspan BMS inspection standard and which includes bridge structure condition ratings and rehabilitation costs. There has been no previous research on a regional Irish bridge stock of this magnitude. Research objectives are the consolidation of the dataset into a usable format, the review of previous research and the formulation of a methodology for the development of a network wide bridge rehabilitation strategy model. A procedure proposed by previous research on the prioritisation of theoretical bridge rehabilitation projects on the Chilean road network has been built upon. Statistical analysis of both recent rehabilitation projects in County Cork and of a survey of experts has led to the formulation of rehabilitation project prioritisation indices. The application of these derived indices allows the forecasting and calculation of funding requirements for network wide improvements. A review of the functional life expectancies of bridges has been undertaken. A deterioration rate which predicts the annual disimprovement in condition rating of each bridge has been calculated using statistical regression analysis and provides a basis for the estimation of investment requirements for an overarching rehabilitation strategy. An economic assessment of four rehabilitation intervention strategies has been undertaken using the Net Present Worth method. A system performance method developed in this research and which uses efficiency and effectiveness indicators taken from UK, New Zealand and French practice has determined that the range of annual investment amounts equivalent to 0.27% and 1% respectively of the bridge stock replacement cost are required to achieve full bridge network rehabilitation and provide a minimum 85 year service life for all structures. A benchmarking comparison with reported international practice has confirmed the applicability of the developed methodology.

## Acknowledgements

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## 1.0 Introduction.

Highway bridges experience deterioration due to natural hazards, ageing, and increased structural performance demands. In a climate of scarce financial resources, managers of highway bridges face challenges in maintaining a safe and efficient network and have to be effective in their management strategies. A bridge network is an integral part of the transportation infrastructure and, consequently, plays a major role in economic development and quality of life. Typically bridges comprise about 2% of a road network's length and about 30% of its value (PIARC, 1996). Due to their critical function, partial or total bridge closure can result in major disruption such as long diversions, congestion and even the total isolation of certain areas. The challenge in bridge management is to ensure that all bridges in a network remain fit for purpose over their service life at a minimum lifecycle cost.

This purpose of this research is the development of a bridge rehabilitation strategy model as a decision making aid to bridge owners. The National Roads Authority (now Transport Infrastructure Ireland (TII)) has developed Eirspan as the Irish bridge management system (BMS) (Duffy, 2004). A recently available dataset of 1,367 Eirspan BMS inventory and principal inspection records provides the opportunity for an in-depth analysis of a regional bridge stock with a rehabilitation cost estimate of €24.2 million and where 26% have suffered at least significant damage and 86% have suffered at least some damage. There has been no previous research undertaken on a regional Irish bridge stock of this magnitude.

## 1.1 Research aim and objectives.

This aim of this research is the development of a bridge rehabilitation strategy model as a decision making aid to bridge owners that will allow the assessment of the condition of the overall bridge stock and the optimisation of bridge rehabilitation strategies at a network level under the constraints of limited budgets and resources. The objectives of the research are:

- the compilation and consolidation of the dataset into a usable format,
- descriptive statistical analyses of the dataset to establish previously unknown characteristics and features,
- the formulation of a procedure for the identification of the best strategy for bridge rehabilitation on a highway network, which recognises the decision problems faced by the bridge owner with respect to:
  - the nature of bridge deficiencies,
  - the requirement for the prioritisation of rehabilitation projects,
  - the uncertainty of future deterioration of bridges,
  - the limitations on funding resources.
- the application of the developed procedure to the available dataset,
- the comparison and benchmarking of the outcome of the developed strategy with international practice and experience.

## 2.0 Literature review.

This research proposes a decision support system for bridge owners in the selection of the best strategy for bridge rehabilitation on a highway network based on an available bridge management system dataset. The literature review focuses on bridge management systems and on the constituent parts of the decision-support model proposed.

### 2.1 Bridge management systems.

Infrastructure, in its simplest terms, is the “basic physical and organisational structure needed for the operation of a society or enterprise, or the services and facilities necessary for an economy to function” (Information Resources Management Association, 2015, p.394). A large percentage of existing civil engineering infrastructure worldwide is deteriorating due to age, harsh environmental conditions and insufficient capacity (Bordogna, 1995). Highway bridges are key elements of infrastructure and Freudenthaler et al. (2008) state that the main global transportation networks have about 2.5 million bridges and, while bridge management systems rate them by various methodologies and approaches, approximately 10% or 250,000 bridges are structurally deficient.

The American Society of Civil Engineers (ASCE, 2017) states that of the 614,387 bridges in the United States in 2016, almost 40% were over 50 years old and 9.1% were structurally deficient. The estimated cost of U.S. bridge rehabilitation is $123 billion and annual investment in bridge rehabilitation is of the order of $18 billion. In an Irish context, Engineers Ireland (2016) states that reduced budget means that national and local authorities have insufficient resources to maintain their road networks to an acceptable condition.

Highways and their bridges are important components of municipal infrastructure and the management of these assets may be defined as:

A systematic process of maintaining, upgrading, and operating assets, combining engineering principles with sound business practice and economic rationale, and providing tools to facilitate a more organized and flexible approach to making the decisions necessary to achieve the public's expectations (OECD, 2001, p.35).

The aim of an asset management system is to assist the road network administration in the process of planning and optimising the operation, maintenance, repair, rehabilitation and replacement of the network and its assets (pavement, bridges, tunnels, equipment, etc.) in the most cost-effective way while minimising the consequences of traffic disruption (PIARC, 2005).

The application of the principles of asset management has led to the development of bridge management systems. Sanford et al. (1999) state that the collapse of the Silver Bridge over the Ohio River in the United States in 1968 led to the introduction of the National Bridge Inventory (NBI) and trace the evolution of inspection, data collection procedures and practice for BMSs through the 1983 failure of the Mianus River Bridge in Connecticut and the 1987 collapse of the Schoharie Creek bridge in New York State.

Czepiel (1995) states that a bridge management system is a rational and systematic approach to the organising and carrying out of the activities related to planning, designing, constructing, maintaining, rehabilitating, and replacing bridges. A BMS is therefore a repository or database of information on the bridges within a particular stock, with data being continuously updated from inspection and maintenance records.

Vassie and Arya (2008, pp. 598-599) report that the original or first generation BMSs consisted of only an inventory whose primary function was the secure storage and easy retrieval of data on individual bridges. Subsequent developments responded to the need to store information about inspections and maintenance work and could be described as second-generation BMSs. Third-generation BMSs have the general objective of maintaining the functionality of the stock at a minimum lifetime cost. This objective requires:

- modules providing information on the economics of maintenance methods and their impact on the flow of traffic,
- algorithms for finding the rate of deterioration and optimising and prioritising maintenance programmes for the bridge stock.

Das (1998) writes that bridge management systems are broadly based on two principles, firstly that bridge maintenance needs are directly related to the condition states of the structures and, secondly, that the justification for any proposed work is that it will cost more in the future if the work is not carried out in the present.

A BMS may be further described as a software tool developed to support activities in the asset management of highway bridges (Halfawy et al., 2006). The functional output is to:

- enable efficient and systematic collection, storage, interrogation, retrieval, management, analysis, and reporting of asset information,
- increase operational efficiency by aiding in the planning, execution, and coordination of maintenance operations,
- assist in coordinating and optimizing the allocation and distribution of maintenance budgets.

In the USA, the Federal Highway Administration has developed the PONTIS bridge management system software package (Thompson et al., 1998; Cambridge Systematics, 2001), which has been adopted by about forty state highway authorities. Zonta et al. (2007) describe PONTIS as one of the most advanced BMSs in use. Also in the United States, the BRIDGIT bridge management system (Hawk and Small, 1998) has been developed mainly to address the needs of smaller highway authorities. The EU-funded BRIME research project (Woodward et al., 2002) reviewed bridge management in Europe and found that eight of the eleven states examined used a computerised bridge management system. Ryall (2010) has compiled a sample list of bridge management systems in use around the world; the information is consolidated in Table 2.1.

The National Roads Authority (now Transport Infrastructure Ireland (TII)) developed Eirspan, which is a customised version of the Danish DANBRO system, as the Irish bridge management system in 2001 (Duffy, 2004).

**Table 2.1 Bridge management systems in use (Ryall, 2010, p.31).**

| Country | Bridge Management System |
|---|---|
| Denmark | DANBRO (DANish Bridges and Roads) |
| Finland | FinnRABMS (Finnish National Roads Administration Bridge Management System) |
| Holland | DISC |
| Italy | SAMOA (Surveillance, Auscultation and Maintenance Of Structures) |
| South Africa | BMS.NRA (National Roads Authority) |
| | SIHA |
| Sweden | BMS (Swedish National Road Administration) |
| United Kingdom | STEG (STructures REGister) |
| | HiSMIS (Highway Structures Management Information System) |
| | SMIS (Structures Management Information System) |
| | BRIDGEMAN (BRIDGE MANagement system) |
| | COSMOS (Computerised System for the Management Of Structures) |
| United States of America | PONTIS (Preservation, Optimisation and NeTwork Information System) |
| | BRIDGIT (BRIDGe Information Technology) |
| | PENBMS (PENnslyvania Bridge Management System) |

## 2.2 Bridge management systems and the development of rehabilitation strategies.

Czepiel (1995) has listed some of the basic elements of a typical BMS as:

- the database module,
- the performance prediction or deterioration module,
- the optimisation or project prioritisation module.

This research uses these three elements to inform the development of a rehabilitation strategy and each element is reviewed in this section.

### 2.2.1 Bridge management system database.

The BMS database is a large collection of indexed digital information that is organised so that it can be easily accessed, managed and updated. Typical information held in a BMS database is:

- bridge inventory, which records the name, location, function, construction type and geometric details of each individual bridge;
- inspection records, where inspection activity records are maintained;
- cost information, where repair and rehabilitation cost estimates, both on a project and network basis, are stored;
- maintenance records, where maintenance activities are kept up to date;
- bridge condition assessments, which describe the state of the components as well as the deterioration of each structure relative to its condition as originally constructed. This description, generally termed the 'condition rating', provides a categorical numerical representation of the condition of the components based on a defined standard and provides a uniform method for describing their condition and functionality.

The database provides an insight into the current condition of a bridge stock and is the starting position in the formulation of a rehabilitation strategy.

### 2.2.2 Bridge deterioration.

Modern design standards invariably specify a design life for bridge structures. In the United States, a design life of 75 years is stipulated (AASHTO, 2017, p.1-2). The New Zealand Transport Agency (2013, p.2-2) requires a design life of 100 years. Transport Infrastructure Ireland states that the design life for all highway structures is to be 120 years

(TII, 2016, p.3). While design life may be prescribed before the construction stage, it is inevitable that highway infrastructure loses functionality over time and the service life of assets is finite.

Lemer (1996) writes that:

> Asset life in general refers to the time until an asset must be replaced due to substandard performance, technological obsolescence, regulatory changes, or changes in society behaviour and values.

Bridge stocks are made up of structures of varying ages with many being built long before design standards evolved. Actual bridge service life has been reported by a number of commentators. The Organisation for Economic Co-operation and Development (OECD, 1992) undertook an international review of bridge service lives and has reported a range from 43 years in Japan to 95 years in Switzerland. In the United States, bridge service lives in a number of states have been reported upon:

- in Indiana, it was estimated that, assuming minor maintenance, concrete and steel bridges would survive 50 and 65 years, respectively (Gion et al., 1993);
- a typical bridge life in Massachusetts of 60 years was reported (Massachusetts Infrastructure Investment Coalition, 2005);
- the Colorado Department of Transportation estimate an average service life of 56 years for its bridge stock (Hearn and Xi, 2007).

In the Netherlands, bridges typically survive from 80 to 100 years (van Noortwijk and Klatter, 2004). Caner et al (2008) have determined an average life of 80 years for bridges on the Turkish road network.

Morcous et al. (2002) state that several infrastructure deterioration models have been developed since the early 1970s (specifically for road pavements) to assist decision-makers in predicting the future condition of a network of facilities. There is a number of approaches with varying degrees of sophistication to modelling bridge deterioration. Agrawal and Kawaguchi (2009) broadly categorised these into three categories that are not mutually exclusive:

- Deterministic models, which are dependent on a mathematical or statistical formula for the relationship between the factors affecting bridge deterioration and the measure of a bridge's condition. The output of such models is expressed by deterministic values (i.e. there are no probabilities involved) that represent the average predicted conditions. The models can be developed by using straight-line extrapolation, regression, and curve-fitting methods (Hatami and Mourcous, 2011).
- Stochastic models, which treat the bridge deterioration process as one or more variables that have a random probability distribution that may be analysed statistically but may not be predicted precisely. Kotze et al. (2015, pp.15-16) state that for bridge deterioration, stochastic models can be classified as either:
    - state-based models, where the deterioration process is modelled through a probability of transition from one condition state to another in a discrete time period. Given that the deterioration process is dependent on a set of measurable variables such as annual average daily traffic (AADT), climate and age, Markov chains have been used extensively in these models.
    - time-based models, where the duration that a bridge element remains at a particular state (condition state) is modelled as a random variable using various probability distributions, such as Weibull distribution, to describe the deterioration process.
- Artificial intelligence models, which exploit computer techniques that aim to automate intelligent behaviours. Artificial intelligence techniques comprise, among others, expert systems, artificial neural networks and case-based reasoning (Agrawal and Kawaguchi, 2009).

### 2.2.3 Prioritisation of rehabilitation projects.

The purpose of project prioritisation is to evaluate rehabilitation projects and rank them in order of urgency or importance. Shah et al. (2013) reviewed prioritisation models for road pavement maintenance management decisions and reported a wide spectrum of methods and approaches in use, ranging from simple priority lists based on engineering judgment to complex network optimisation models. These methods are transferrable to the prioritisation of bridge rehabilitation projects. The authors divided this range of prioritisation methods into four main groups:

- Ranking methods: The ranking of assets for maintenance is done on the basis of a priority index calculated by combining different attributes or characteristics. These attributes may be estimated by considering parameters such as importance on the road network, structural condition, traffic volumes, economic analysis, road functional class, and engineering judgement.
- Optimisation methods: Priority programming by optimisation combines the function of priority programming, program formulation, and project scheduling into one operation, which gives the optimum schedule of projects through precise analytical techniques such as linear and dynamic programming. Generally, these methods use maintenance cost minimisation or maintenance benefits maximisation to generate the optimal maintenance plans.
- Artificial intelligence techniques: These techniques include fuzzy mathematical programming, artificial neural networks, and evolutionary computing and are particularly appropriate where the information may be uncertain and incomplete.
- Analytical hierarchy process method: This is a multi-criteria decision-making approach which can be used to solve complex problems. The method provides a process for comparing alternatives by structuring criteria into a hierarchy, providing for pair-wise comparisons of criteria at the lowest level of the hierarchy, and synthesising the results into a single numerical value.

Wakchaure and Jha (2011) report that bridge maintenance priority indices are commonly used. The basic principle behind the indices is to rank the bridges for maintenance priority based on characteristic attributes, such as:

- the importance of a bridge on a road network, which may be described in terms of criteria such as road category, annual average daily traffic or detour distance, and
- an assessment of the bridge condition, which may be described in terms of criteria such as structural stability, remaining life or general condition.

The general form of a maintenance priority index (Hearn, 1999; Gralund and Puckettt, 1996) is:

$$\mathbf{PI} = \sum_{\mathbf{i=1}}^{\mathbf{n}} \mathbf{K_i}\,\mathbf{f_i}(\mathbf{a}, \mathbf{b}, \mathbf{c} \dots .) \qquad (\mathbf{1})$$

where PI is the maintenance priority index;
$K_i$ are weighting factors for each criterion considered;
$f_i\,(a, b, c, \dots)$ are the functions that describes each criterion used; and
a, b, c... are the bridge condition or goal parameters.

Amini et al. (2016) investigated attribute factors for the rehabilitation priority of urban bridges in the Iranian city of Tehran through a literature review of previous international research and from statistical analysis of a survey of experts. Four main parameters (environmental conditions, structural condition, cost and strategic value) were derived, which in turn were broken down into 45 sub-factors.

The entire bridge stock is treated as one large system containing the summation of component bridge attributes, their condition states or other prevailing characteristics at the time of inspection. Bridge maintenance priority indices have been the focus of previous research internationally using a range of parameters:

- Load capacity, remaining life, deck width, horizontal and vertical clearances have been used by different states in the USA for the development of ranking formulae (Gralund and Puckett, 1996).
- In Greece, structural defects, traffic volume, environmental conditions, bridge age, river bed characteristics and foundation and superstructure type have been used by

Chassiakos et al. (2005) for developing a priority index. The index was initially formulated based on the experience of the road authority and was adjusted by a trial-and-error technique. The application of the system was demonstrated on 10 bridges on the road network in Western Greece.

- Hai (2008) in Vietnam has taken into consideration structural condition, location, width, traffic volumes and budget constraints for the determination of bridge importance and illustrated the method by its application to 29 bridges.
- In Thailand, Rashid and Herabat (2008) proposed a priority index based on level of service, structural condition, safety, cost, socioeconomic value and fuel consumption. The index was compiled from an analysis of responses to a survey from nine expert practitioners from highway agencies in Thailand.
- Valenzuela et al. (2010) considered the annual average daily traffic, length and width of bridges, availability of alternative routes, social and economic development of the area and load restriction to develop an index for bridges on the Chilean road network. The index was derived from a survey of 20 experts and applied to six bridges on the primary road network.
- In Australia, Rashidi et al. (2013) investigated the structural condition of bridge components, the vulnerability and location of the bridge, bridge age, road classification, number of lanes, the width of the deck, vertical clearance and the social implications of rehabilitation in the development of a ranking method for the remediation of concrete bridges.

## 2.3 Bridge rehabilitation strategy performance model.

The objective of a bridge rehabilitation strategy is the efficient and cost effective maintenance and repair of structures to maximise the service lives of bridges on the road network. Such a strategy had been described by Sinha and Labi (2011, p. 520) as being "expected to provide a mechanism for selecting cost-effective projects reflecting community needs and to develop a multi-year investment strategy within budgetary constraints over a planning horizon". A model has been described by Qureshi et al. (1999) as "a representation of an object, system or idea in some form, other than that of the entity itself. Its purpose is usually to aid in explaining, understanding or improving performance of a system”. The aim of this research is to develop a strategy in the form of a model that will provide a rational basis for the delivery of a high performing policy for the maintenance and rehabilitation of a regional bridge stock.

The American management expert and academic, Peter Drucker, is credited with the statement that “it is not possible to manage what you cannot control and you cannot control what you cannot measure” (Weber and Thomas, 2005, p.3). Performance measurement is therefore a fundamental principle of management and, within the bridge management process, the identification of rehabilitation strategies is more effective when developed in a uniform and repeatable manner. This can be accomplished by performance indicators, which improve the planning of bridge maintenance strategies (Strauss et al., 2016). For this research, the performance indicators of ‘effectiveness’ and ‘efficiency’, and their combination in terms of ‘performance’, are considered in the assessment of strategy options and used to identify the optimal bridge stock rehabilitation strategy.

Effectiveness is defined by the British Standards Institution as the “extent to which planned activities are realised and planned results are achieved” (BSI, 2015, p.22). It is thus a measure of the outcome of a strategy and can be described as the ratio of realised achievement and the planned target. Johnston (1996) describes ‘effectiveness’ as ‘output’ divided by ‘standards’. This research uses the Bridge Stock Condition Index (BSCI) concept of a single numerical value to describe the condition of a bridge stock and is described by the UK County Surveyors’ Society (Atkins, 2002) as the measure of effectiveness. An increase in the BSCI following the implementation of a rehabilitation strategy shows measurable effectiveness, while a decrease shows ineffectiveness.

The term ‘efficiency’ is reported as the “relationship between the result achieved and the resources used” (BSI, 2015, p.22). It is therefore a measure of economic cost and can be described as the ratio of a defined objective realised and the resources required in achieving this objective. Johnston (1996) describes ‘efficiency’ as ‘output’ divided by ‘input’. The efficiency concept in the formulation of a bridge stock rehabilitation strategy has been applied to bridges on the French national route system by Orcesi and Cremona (2011), who state that the total bridge stock rehabilitation cost indicates the efficiency of a rehabilitation strategy. A similar approach by the New Zealand Transport Agency, which measures the residual asset value of the road infrastructure by the cost of its restoration, is reported by Horak et al. (2001).

There is linkage between the effectiveness and efficiency indicators; Goh (2013) has described the connecting relationship in the matrix format of Figure 2.1. Using this concept, indicators that efficiently pursue the right goals have high efficiency and high effectiveness, while indicators that inefficiently pursue the wrong goals have low high efficiency and low effectiveness.

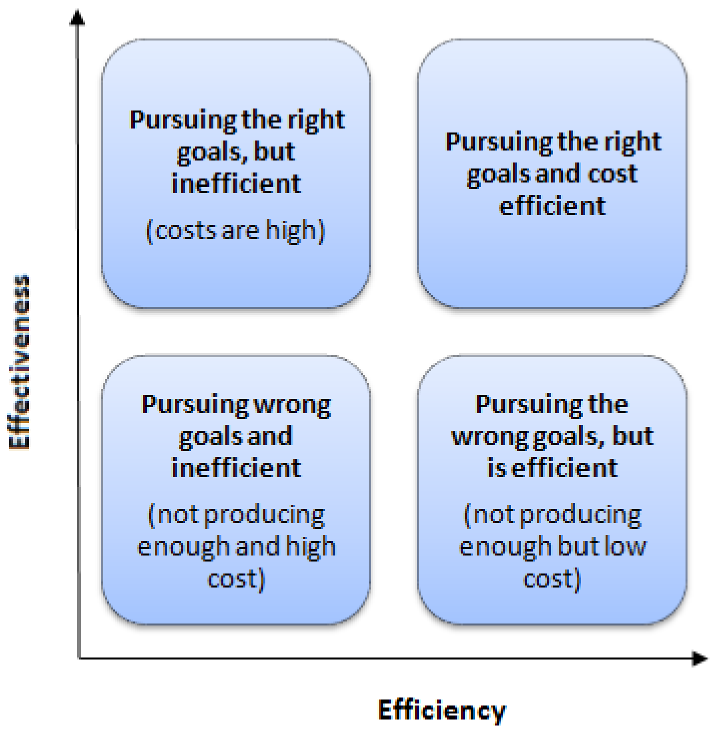



**Figure 2.1. Efficiency and effectiveness relationships (adopted from Goh, 2013).**

McGee (2004) writes that there is an optimum balance between effectiveness and efficiency i.e. a balance between resources and activity, and activity and results. This optimum balance is known as performance, as shown in Figure 2.2. 'Efficiency' is a product of 'resources' and 'activity', while 'effectiveness' is a product of 'activity' and 'results'. 'Effectiveness' and 'efficiency' combine to define 'performance'.

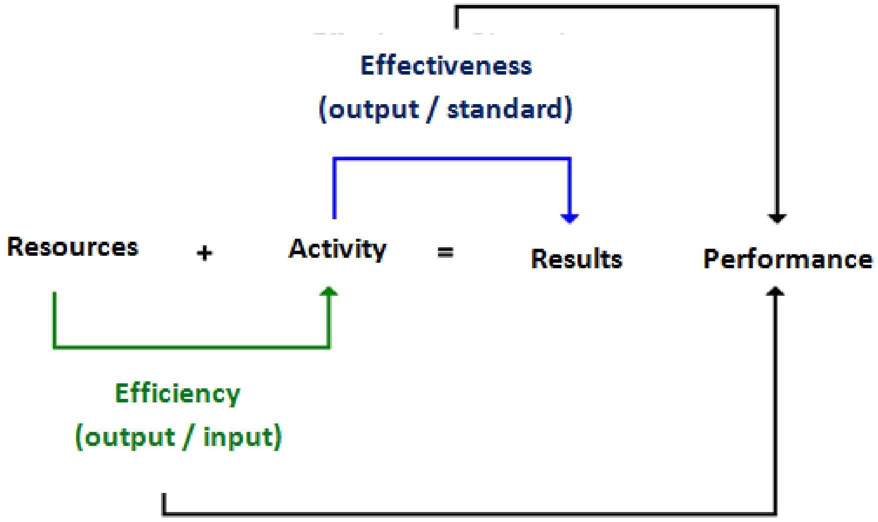



**Figure 2.2. Efficiency, effectiveness and performance**

**(adopted from McGee, 2004).**

To inform the development of a strategy performance model and to provide benchmarks against which it may be measured, a review of international practice shows that there are three main bridge rehabilitation investment strategy approaches in use by road authorities:

- strategy based on improvement targets of condition ratings. In Switzerland, the canton of Grisons (Schellenberg et al, 2016), with a bridge stock in excess of 1,000 structures, has set as annual improvement targets:
  - no more than 5% 'poor' condition rated bridges
  - no more than 20% 'damaged' condition rated bridges.
- strategy based on investment defined as a percentage of replacement costs. Kähkönen and Marshall (1990, p.102) write that the Finnish roads authority spends 0.6% of the value of their bridge assets on the maintenance and repair of bridges and 1% on rehabilitation (defined as widening, strengthening and replacement).

- strategy based on the improvement of a percentage of the total number of bridges. In the United States, the Minnesota Department of Transportation (2014, p.67) reports an annual target of 2% of bridges for repair and preventive maintenance.

Yanev (2007, p.167) states that "the maintenance practices of large asset networks are most revealingly expressed by the ratio of annual maintenance expenditures to the estimated replacement costs". In the United States, the federal government recommends that the annual maintenance and repair budgets for infrastructure assets should be set at approximately at 2% to 4% of the current replacement value (National Research Council, 1996, p.1).

In the case of highway bridges, this approach has been the subject of previous research:

- the World Road Association has undertaken a comparative study on international bridge management activities and established that the ratio of annual maintenance and repair budget to replacement value in eight European countries ranged from 0.24% in Italy to 1.79% in Sweden (PIARC, 2004).
- McCarten (2006), who undertook research into a sample of bridges under the control of the British Columbia Ministry of Transportation in Canada, concluded that a minimum of 0.5% of the bridge stock replacement value is required for annual bridge rehabilitation investment to achieve a 75 year design life for bridges.
- Mirza (2006), also from research on Canada's bridge network, reports that the annual maintenance costs of bridges vary between 0.5% and 1.5% of the construction replacement cost.

## 2.4 Bridge management system data as a research field and gaps in existing knowledge.

In the United States, the Federal Highway Administration compiles and maintains the National Bridge Inventory (NBI); this database is the largest collection of bridge data in the world (Wu and Chase, 2010). The database contains detailed information on more than 600,000 highway bridges recorded over several decades and, with each NBI bridge record containing 116 individual parameters, has a total of up to 70 million data records. Chuang and Yau (2016) state that the Bridge Management System in Taiwan, established in 2000, has an inventory of 28,365 bridges, each with 122 attributes, and a total dataset of up to 3.5 million records.

The Irish Eirspan BMS has 79 fields for data entry for each bridge. For the available dataset of 1,367 bridges under consideration in this research, this provides in excess of 110,000 separate data records. The quantity and quality of information held in BMS databases thus offer considerable potential for academic research and, by exploiting modern computational methods and performing extensive data analysis, have the potential to allow the extraction of information from a large dataset for descriptive, inferential and predictive purposes, using advanced statistical techniques.

A number of gaps in the existing knowledge has been found and addressed in this research:

(i). Eirspan datasets have not to date been the subject of extensive study and investigation. A literature review identifies just one research study undertaken (Hanley et al., 2015), which studied the application of principal component analysis (PCA) on the Eirspan records of 94 bridges.

(ii). The literature has records of studies into the heritage and architectural aspects of Irish bridges, both on a national level (O'Keeffe and Simington, 2016) and regional level (Cork County Council, 2015; Hamond, 2005, 2009; McLoughlin, 2007, 2015). There has, however, been no investigation into the engineering characteristics of an Irish regional bridge stock and no descriptive statistical analysis has been undertaken into the geometry, construction types, damage types, condition ratings or rehabilitation costs of such an asset stock.

(iii). While Heron and Bowe (2010) report on a screening and vulnerability rating system developed for 300 railway bridges managed by Iarnród Éireann, there is no evidence in the literature of a systematic investigation of bridge scour on an Irish regional road bridge stock nor of a comparison with international experience.

(iv). The Eirspan system, in common with many other bridge management systems (Mirzaei et al., 2012), does not predict bridge deterioration rates or determine the best intervention or rehabilitation strategies. It is not current practice to use the collected bridge inspection information to predict future bridge conditions through a deterioration modelling process, which would provide a better understanding of the safety and financial aspects of managing the bridge network. This research develops an approach for the calculation of the annual rate of disimprovement in condition ratings based on international experience. The research further proposes a methodology for project prioritisation which builds on previous studies and thus provides a basis for the identification of the optimum rehabilitation strategy.

(v). This research goes beyond the approach taken by earlier commentators in the formulation of prioritisation indices (Chassiakos et al., 2005; Hai, 2008; Rashid and Herabat, 2008; Valenzuela et al, 2010). Previous research considered only the formulation and application of theoretical indices based on expert surveys; this present research derives a similar index from a record of recent and actual bridge rehabilitations. This has led to a recognition, previously not evident in the literature, that particular motivations and judgements apply in the selection of rehabilitation projects for structures at or close to failure.

(vi). There is no evidence of research into the impact of current levels of investment in bridge rehabilitation in Ireland. A standard economic appraisal method is applied to the dataset and found to have limitations with respect to a multiple project strategy such as a bridge stock rehabilitation process, which is continuously deteriorating. This research reviews international practice and proposes an alternative methodology to determine the optimum investment level required to maintain the bridge stock.

(vii). This research proposes a novel and unique approach to evaluating the success of a rehabilitation strategy by using the concept of a performance, calculated by a comparison of the effectiveness and efficiency indicator parameters. This approach, which is confirmed by comparative benchmarking against published international practice and research, has not been previously applied to the management of bridge stocks.

## 3.0 Outline of research methodology.

An available dataset of 1,367 bridge inspection records for regional and local roads in County Cork, undertaken to the Eirspan BMS inspection standard and which includes bridge structure condition ratings and rehabilitation costs, formed the basis of the research. Details of rehabilitation projects recently undertaken by the highway authority, once the condition of the surveyed bridges become known, were also used in this research. The research methodology as a set of sequential steps is presented graphically in Figure 3.1.

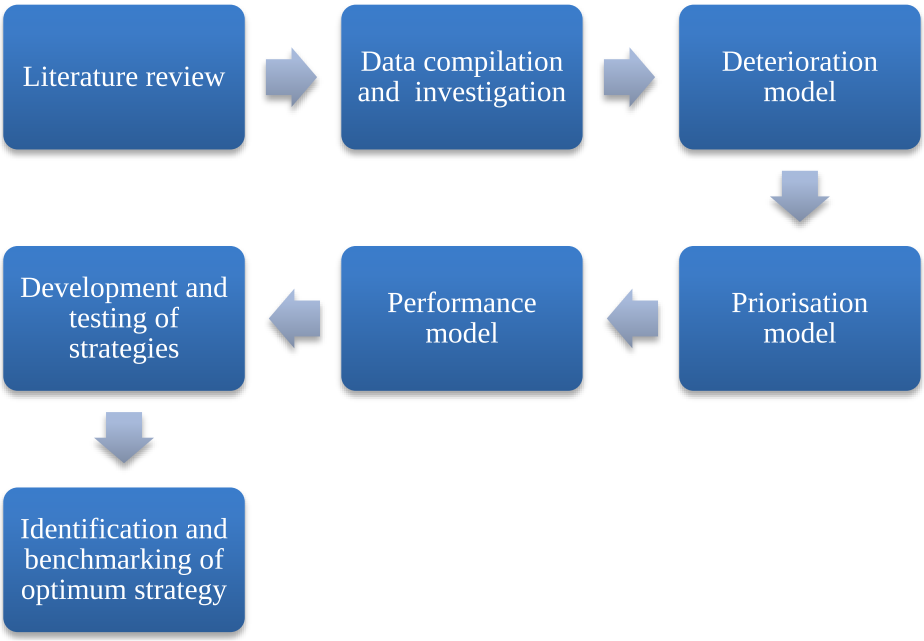



**Figure 3.1 Research methodology.**

### (i). Literature review.

A literature review investigated bridge management systems, their evolution, characteristics and application in the field of asset management. Current practice and research in deterioration and project prioritisation modelling were explored and summarised. The concept of system performance and its application to rehabilitation strategies were identified.

**(ii). Study area background, data compilation and investigation.**

The characteristics of the study area were summarised and its national importance in terms of road lengths, river lengths and number of bridges highlighted. The Eirspan BMS and its key elements were described. The raw survey data were compiled and integrated into a usable tabular format and information extracted to discover previously unknown trends, patterns and relationships. The Microsoft Excel spreadsheet application was used to consolidate the dataset and to produce descriptive statistics on the geometry, construction materials, damage types, condition ratings and rehabilitation costs of the bridge stock. A review of damage types was undertaken by Pareto analyses (Montgomery, 2009, p.40) and the main types identified in an Ishikawa or ‘cause and effect’ diagram (Montgomery, 2009, p.203). The high frequency of bridge scour as a deterioration mechanism was explored and compared with international experience. The total bridge stock rehabilitation cost was calculated and a review of recent new bridge construction projects in Ireland informed a cost estimate of the financial value of the subject bridge stock. A comparison with contemporaneous data for national road bridges was undertaken and a commentary given on the differences in bridge type and condition ratings. Bridge rehabilitation projects of poorly rated bridges in the study area during the four year period 2014 to 2017 were described in terms of cost, numbers, rehabilitation techniques and construction challenges.

**(iii). Deterioration model.**

A review of published international functional life expectancy values of bridges was undertaken. European data, with an emphasis on similar bridge stocks, have been investigated using the regression analysis capability of the SPSS (an acronym for ‘Statistical Package for the Social Sciences’) statistical software package (IBM, 2016) to formulate a deterministic linear model to estimate bridge life expectancy and to predict the annual deterioration rate in condition rating terms of each bridge asset.

**(iv). Prioritisation model.**

A procedure for the prioritisation or sequencing of theoretical bridge rehabilitation projects on the Chilean road network was identified and replicated. A survey of 33 expert practitioners was undertaken, the survey results analysed and, by statistical analysis of a random sample of bridges, a priority index formulated. Statistical analysis of the characteristics of recent rehabilitation projects undertaken on structures at or close to failure led to the formulation of a separate priority index. The statistical analyses were undertaken using SPSS software. The research suggests that two indices exist, one for critical (failed and close to failure) bridges and one for non-critical bridges. An overall prioritisation model for the entire dataset was thus determined, with the most severely damaged bridges ranked initially and followed by the less severely damaged structures. The derived indices were applied to all bridges and a priority ranking established.

**(v). Performance model.**

An overall strategy time horizon, made up of a number of separate planning time horizons, was defined by the results of the deterioration model and confirmed by comparison with reported planning periods for transportation projects in the literature. A standard economic appraisal method was identified and described. Research into international practice identified the performance parameters of efficiency and effectiveness, taken from UK, New Zealand and French methods, as being determining factors in proposing the concept of system performance in the evaluation of the success of a rehabilitation strategy and the identification of an optimal strategy.

**(vi). Development and testing of strategies.**

Five strategies were developed and investigated:

- Strategy 1, which was the baseline or reference scenario with no annual investment and where all bridges deteriorate to failure at the end of the strategy time horizon.
- Strategy 2, which represented the minimum investment required to achieve rehabilitation of all structures of the bridge stock within the strategy time horizon.
- Strategy 3, which represented the existing investment strategy being implemented.
- Strategy 4 and Strategy 5. Annual investment values expressed as percentages of a bridge stock replacement cost and reported in practice and from research internationally were used to develop these strategies.

A statistical procedure to determine the cost increases associated with bridge deterioration from a particular condition rating to a higher rating was used.

**(vii). Identification and benchmarking of optimum strategy.**

The characteristics of the five developed investment strategies with respect to cost, time and number of construction projects per annum were calculated. A standard economic appraisal method was applied and its limitations described. The performance parameters of effectiveness and efficiency were measured for each strategy. The evaluation of the performance indicators using the concept of system performance identified the minimum and optimum investment levels required to achieve the process goals. A benchmarking comparison with reported international practice was undertaken to test the applicability of the developed methodology.

Conference papers published during the course of this research are included in Appendix A.

## 4.0 Data analysis and statistical methods.

Data analysis is the process by which numerical data are transformed into a useable form for scientific interpretation. This research makes extensive use of the IBM SPSS statistical analysis software package (IBM, 2016). The SPSS software program, whose title is an acronym for ‘Statistical Package for the Social Sciences’, was developed for the analysis of statistical data in the social sciences. However, because of its capabilities, it is also extensively used by market researchers, scientists, health-care researchers, survey organisations, governments and statistical analysis professionals. The package can be used to analyse data collected from surveys, tests and observations and it can perform a variety of data analyses and presentation functions.

Two main statistical methods for data analysis are employed in this research:

1. Descriptive statistics, which are used to calculate, describe and summarise collected research data in a logical, meaningful and efficient way (Vetter, 2017). This research seeks in several instances to establish the ‘average’ or ‘central tendency’ value of a number of data samples. There are three measures of central tendency (Field, 2009, pp.789-790):
   - the mean, which is the arithmetic average of data and is expressed by the equation:

$$\bar{\mathbf{x}} = \frac{\sum_{i=1}^{n} x_i}{\mathbf{n}} \qquad \textbf{(2)}$$

     where $\bar{x}$ equals the mean, $x_i$ represents each individual data point and n is the number of data points in the sample.

   - the median, which is the "mid-most" value of a data distribution and is the value above which or below which half of the data points lie.

- the mode, which is the most commonly obtained value or values on a data scale, or the highest point of a peak on a frequency distribution.

Measures of central tendency do not describe the variability, or spread, of data. Several estimates of variability exist:

- the range, which is the interval between the lowest and highest values within a data group.
- the interquartile range, which is the range of values that contains the middle 50% of the scores. The lower bound of the interquartile range is called the first quartile (Q1) i.e. 25% of the scores have a value lower than Q1 and 75% of the scores have a value larger than Q1. The upper bound of the interquartile range is called the third quartile (Q3) i.e. 75% of the scores have a value lower than Q3 and 25% of the scores have a value larger than Q3.
- the standard deviation, which is one of the most commonly used estimates of data variability and is integral to the performance of inferential statistical techniques. Standard deviation ($\sigma$) is calculated using Equation 3:

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2} \qquad \textbf{(3)}$$

where $x_i$ represents each individual data point, $\bar{x}$ represents the mean and n is the number of data points in the sample.

The importance of the standard deviation lies in its relationship to the Gaussian, or normal, distribution. The normal distribution is useful because of the central limit theorem, which states that given a sufficiently large sample size from a population with a finite level of variance, the mean of all samples from the same population will be approximately equal to the mean of the population. This research tests a number of data samples for normality using SPSS. The methods used are:

- visual inspection of:

- the histogram of these data, which is an representation of the frequency distribution of numerical data and provides an estimate of the probability distribution of a quantitative variable. A histogram, such as that shown in Figure 4.1, which is symmetrical with a single central peak at the mean of the data that forms the shape of a bell curve and has 50% of the distribution to the left of the mean and has 50% to the right of the mean has the general characteristics of a normal distribution.

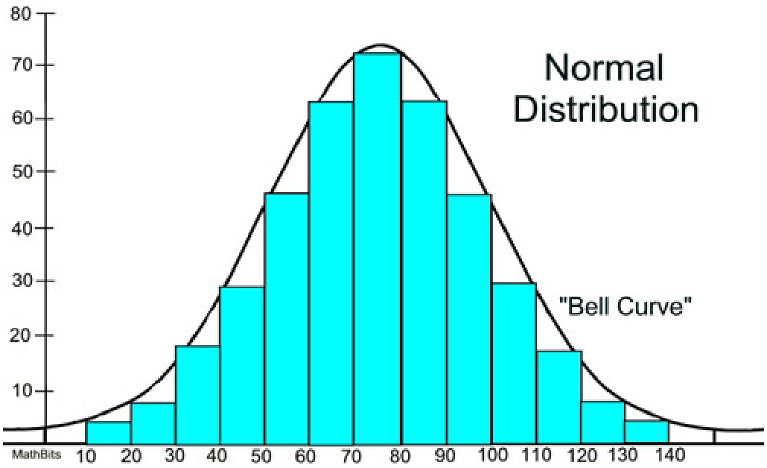



**Figure 4.1. Histogram and normal distribution (MathsBitsNotebook, 2019).**

- normal Q-Q (quantile-quantile) plot of these data, which is a graph of the quantiles (cut points dividing the range of a probability distribution into continuous intervals with equal probabilities of a variable) against the quantiles of a particular distribution (generally a normal distribution). If values fall on the diagonal of the plot, then the variable shares the same distribution as the one specified. Deviations from the diagonal suggest a difference from the distribution of interest. Figure 4.2 shows a QQ-plot generated by SPSS that indicates that observed values conform well to the expected normal values and it may be inferred that the observed values are likely to follow a normal distribution.

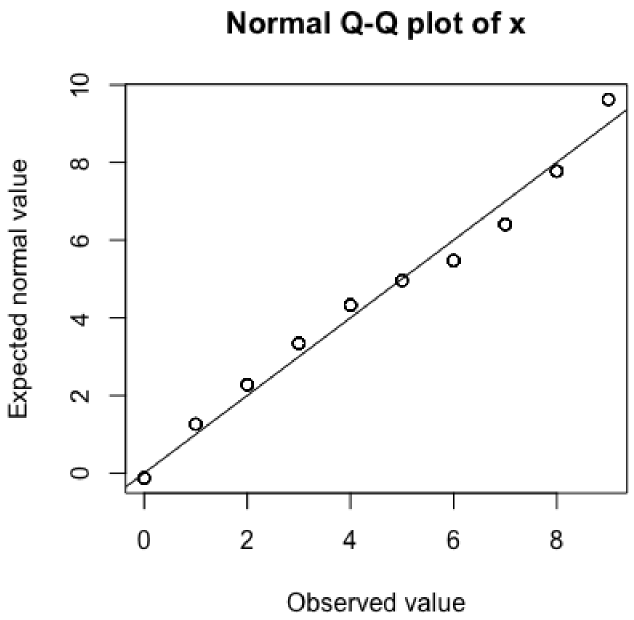



**Figure 4.2. Q-Q plot generated by SPSS (Heckman, 2019).**

- the box-plot (or box-and-whisker plot) of these data, which is a method for graphically depicting important features of numerical data, such as location or central tendency, spread or variability, departure from symmetry, and identification of observations that lie unusually far from the bulk of the data (these observations are called "outliers"). Figure 4.3 is an example of a box-plot for a normal distribution and displays the quartiles on a rectangular box, aligned horizontally. The box encloses the interquartile range (IQR) with the left-hand line at the first quartile, $Q_{0.25}$, and the right-hand line at the third quartile $Q_{0.75}$. A vertical line at either end, usually called whiskers, is drawn at $Q_{0.25}$ - 1.5 IQR and $Q_{0.75}$ + 1.5 IQR and data points outside of these limits are termed outliers.

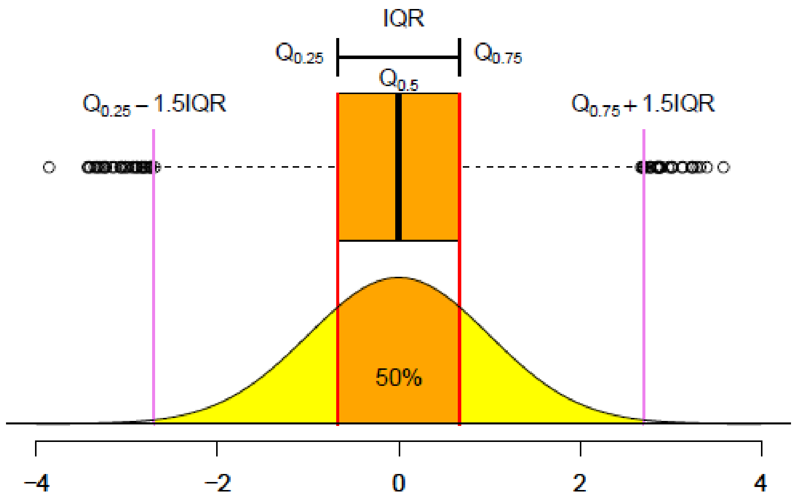



**Figure 4.3. Example of a box-plot for the standard normal distribution.**

**(Burgard, 1983, p.100)**

- statistical tests of normality that provide evidence of the extent to which a sample distribution is statistically different from a normal distribution:
  - the Kolmogorov–Smirnov (K-S) test is a non-parametric test that assesses the degree of agreement between an observed distribution and a theoretical continuous distribution. This statistic quantifies a distance between the empirical distribution function of a sample and the cumulative distribution function of the reference distribution, or between the empirical distribution functions of two samples (Arsenault, 2017). The Kolmogorov–Smirnov statistic for a given cumulative distribution function F(x) is:

$$D_n = sup_x|F_n\ (x) - F(x)| \tag{4}$$

where $sup_x$ is the least upper bound of the set of distances and $F_n$ is the empirical distribution function for n independent and identically distributed observations.

  - the Shapiro-Wilks (S-W) test, which indicates whether a distribution of scores is significantly different from a normal distribution. A significant value indicates a deviation from normality (Field, 2009, p.796). The test statistic is calculated using the formula:

$$W = \frac{(\sum_{i=1}^{n} a_i \, y_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \qquad (\mathbf{5})$$

where:

$y_i$ is the $i^{th}$ order statistic;

$\bar{y}$ is the sample mean;

$$a_i = (a_1, \dots a_n) = \frac{m^T V^{T-1}}{(m^T V^{-1} m)^{0.5}} \qquad (\mathbf{6})$$

$m = (m_1,...m_n)^T$ are the expected values of the order statistics of independent and identically distributed random variables sampled from the standard normal distribution; and

V is the covariance matrix (Razali and Wah, 2011).

The Shapiro-Wilks test is recommended for use with small sample sizes ($n < 50$).

For both tests, if the test result is non-significant ($p > 0.05$), the distribution of the sample is considered normal (Hahs-Vaughn and Lomax, 2013, p.148).

- calculation of z-values (i.e. measures of standard deviation) for both skewness and kurtosis, where each parameter is divided by its respective standard error. Skewness characterises the degree of asymmetry of a distribution around its mean (Press et al., 2007, p.723) and may be expressed mathematically for a dataset of $x_0,\dots, x_{N-1}$ as:

$$\mathrm{Skew}(x_0 \dots x_{N-1}) = \frac{1}{N}\sum_{j=0}^{N-1}\left[\frac{x_j - \bar{x}}{\sigma}\right]^3 \qquad \mathbf{(7)}$$

where $\sigma$ is the standard deviation, $x_j$ represents each individual data point and $\bar{x}$ represents the mean of the data points in the sample.

Kurtosis measures the degree to which scores cluster in the tails of a frequency distribution and may be calculated (Press et al., 2007, p.724) from the formula:

$$\mathrm{Kurt}(x_0 \ldots x_{N-1}) = \left\{ \frac{1}{N} \sum_{j=0}^{N-1} \left[ \frac{x_j - \overline{x}}{\sigma} \right]^4 \right\} - 3 \qquad \textbf{(8)}$$

where σ is the standard deviation, $x_j$ represents each individual data point and $\overline{x}$ represents the mean of the data points in the sample.

If the calculated z-score is outside -1.96 to 1.96, the data sample is considered to be not normally distributed.

Should the analysed data sample be found to be normally distributed, the mean and standard deviation values are reported. Should the data not be normally distributed, both the median and interquartile range are reported.

2. Inferential statistics, which are defined by Gallin and Ognibene (2012) as the process through which inferences about a population are made, based on certain characteristics calculated from a sample of data drawn from that population. Regression analysis is used extensively in this research and is a statistical modelling technique which investigates the relationship between a dependent or outcome variable and one or more independent or predictor variables**.** This technique is used for forecasting, modelling and finding the cause and effect relationship between the variables. If linear relationships between variables are assumed, a set of theoretical linear equations can be derived by regression methods. Two types of regression analysis have been used in this research:
    a) Simple linear regression analysis, which is a statistical method for obtaining a formula to predict values of one variable from another, where there is a causal relationship between the two variables. The analysis produces a regression equation that can be used in prediction and forecasting and has the form:

$$y = \mathbf{b_0} + \mathbf{b}x + \boldsymbol{\varepsilon} \qquad \textbf{(9)}$$

where $b_0$ is the *y*-intercept, b is the slope and ε is an error term with zero mean and constant variance.

The regression equation is calculated from the data based on the Least Squares Principle, which is a statistical method used to determine a line of best fit by minimising the sum of squares created by a mathematical function. The difference or error between the observed value of the dependent variable (y) and the predicted value (ŷ) is called the residual (e). The residual is the vertical distance (or deviation) from the observation to the predicted regression line.

b) multiple regression analysis, which is similar to simple linear regression but can produce more extensive models by including two or more explanatory variables. The formula for multiple linear regression has the form

.

$$\mathbf{y}_{\boldsymbol{i}} = \mathbf{b_0 + b_1x_1 + b_2x_2 + ... + b_nx_n} + \boldsymbol{\varepsilon}_{\boldsymbol{i}} \qquad \textbf{(10)}$$

where:

$y_i$ is the ith observation of the dependent variable y, i = 1,2,....n;

$b_0$ is the y-intercept or the value of outcome when all explanatory variables are zero;

$b_j$ is the slope coefficient for each of the independent variables, j = 1,2,...........n;

$x_j$ are the independent variables, j = 1,2,...........n;

$\varepsilon_i$ is the error term for the ith observation.

Before a complete regression analysis can be performed, assumptions concerning the original data must be made (Sevier, 1957). Ignoring the regression assumptions contributes to invalid estimates (Antonakis and Deitz, 2011). Meaningful data analysis relies on an understanding and testing of the assumptions and the consequences of violations (Ballance, 2011).

For simple linear regression, Hahs-Vaughn and Lomax (2013, pp.627-632) list the assumptions as:

(i). **Independence of errors.** For any two observations, the residual, i.e. the difference between the predicted and observed values, should be uncorrelated (or independent). This is also described as a lack of autocorrelation. This assumption can be checked using the Durbin–Watson test, which tests for serial correlations between errors. Specifically, it tests whether adjacent residuals are correlated. The size of the Durbin–Watson statistic depends upon the number of predictors in the model and the number of observations. The test statistic can vary between 0 and 4 with a value of 2 meaning that the residuals are uncorrelated (Field, 2009, pp.220-221). A value greater than 2 indicates a negative correlation between adjacent residuals, whereas a value below 2 indicates a positive correlation. The Durbin–Watson statistic (d) can be calculated using the formula:

$$d = \frac{\sum_{i=2}^{n} (e_i - e_{i-1})^2}{\sum_{i=1}^{n} e_i^{\,2}} \qquad \textbf{(11)}$$

where $e_t$ is the difference between the estimated point and the actual point and $n$ is the number of data points.

(ii). **Homogeneity of variance.** At each level of the predictor variable, the variance (i.e. the average of the squared differences from the mean) of the residual terms should be constant. This means that the residuals at each level of the predictor should have the same variance (homoscedasticity); when the variances are very unequal there is said to be heteroscedasticity. This assumption can be tested by an examination of a scatter plot of the regression standardised residuals against the regression standardised predicted values, where no point is to be outside -3 to 3 (Grande, 2015; Field, 2009, p.216).

(iii). **Normality.** It is assumed that the residuals in the model are random, normally distributed variables with a mean of 0. The assumption of normality is tested by either a Shapiro-Wilks or Kolmogorov–Smirnov normality test ($p > 0.05$), both described earlier in this section, and visual inspection of the histogram, normal Q-Q plot and box plot examination of the standardised residuals.

(iv). **Linearity.** The dependent variable is assumed to have a roughly linear relationship with each of the independent variables, taking into account any other explanatory variables in the model. This assumption is tested by examination of a scatter plot of the independent and dependent variables.

In the case of multiple regression analysis, O'Brien and Sharkey-Scott (2012) report that the assumptions (i) to (iv) apply, as well as three further assumptions:

(v). **Sample Size.** The literature provides a number of methodologies for establishing the required size of samples for multiple regression analysis (Chatfield, 1988; Tabachinick and Fidell, 2007; Faul et al., 2014). The approach taken in this research is to adopt the recommendation of Field (2009, p. 222) that, for each explanatory variable in the model, 15 cases of data are required.

(vi). **Multicollinearity of independent variables.** Multicollinearity occurs when two or more independent variables are highly correlated with each other. For multiple regression analysis, there should be no perfect linear relationship between two or more of the predictors. This assumption is tested by an examination of the Pearson product-moment correlation coefficient values and is a measure of the linear association between two variables x and y. It has a value between -1 and 1 where:

- 0 indicates no linear correlation between two variables,
- 1 indicates a perfectly positive linear correlation between two variables.

The Pearson correlation coefficient (r) may be calculated using the formula:

$$r = \frac{\sum_{i=1}^{n}\left(\left(x_i - \bar{x}\right)\left(y_i - \bar{y}\right)\right)}{\sqrt{\sum_{i=1}^{n}\left(x_i - \bar{x}\right)^2 \sum_{i=1}^{n}\left(y_i - \bar{y}\right)^2}} \quad \textbf{(12)}$$

Table 4.1 describes the interpretation of calculated correlation values.

**Table 4.1. Strength of correlation (Zady, 2000).**

| Value of correlation coefficient | Interpretation |
|---|---|
| **0.90 to 1.00** | Very high correlation |
| **0.70 to 0.89** | High correlation |
| **0.50 to 0.69** | Moderate correlation |
| **0.30 to 0.49** | Low correlation |
| **0.00 to 0.29** | Little if any correlation |

Ntoumanis (2013) and Field (2009, p.657) state that correlation values above 0.7 indicate multicollinearity between independent variables. Collinearity can also be detected by the calculation of a further two parameters:

- Variance inflation factor (VIF), whose value is to be less than 10 (Myers, 1990), and
- Tolerance statistic, which is to be greater than 0.2 (Menard, 1995).

(vii). **Absence of significant outliers, high leverage points or highly influential points.** Outliers are observations with large residuals (the deviation of the predicted from the observed). Leverage measures the extent to which the predictor differs from the mean of the predictor. An influential point is one whose deletion has a large effect on the parameter estimates. Compliance with these assumptions may be investigated by considering three calculated parameters:

- Mahalanobis distances, which are measures of the distance from each case to the mean of the independent variable for the remaining cases. The Mahalanobis distance (MD) of a set of observations $x_i = (x_1, x_2, x_3, ..., x_N)^T$ with mean $\bar{x} = (\bar{x}_1, \bar{x}_2, \bar{x}_3, ..., \bar{x}_N)^T$ and covariance matrix $C_x^{-1}$ may be expressed by the formula (De Maesschalck et al, 2000):

$$MD = \sqrt{(x_i - \bar{x}) C_x^{-1} (x_i - \bar{x})^T} \qquad \textbf{(13)}$$

  The value of the Mahalanobis distance is used as a test statistic value by reference to the Chi-square distribution table, where a comparison of the degrees of freedom of the model and the confidence level provides an indication of a value above which individual points are likely to be outliers. A Chi-square distribution is a probability distribution of the sum of squares of several normally distributed variables and is used to test the fit of models to observed data (Field, 2009, p.782).

- Cook’s distance is a measure of the overall influence of a data point or case on a model when performing a least-squares regression analysis. Data points with large residuals (outliers) and/or high leverage may distort the outcome and accuracy of a regression. Points with a Cook's distance value greater than 1 are likely to be outliers (Ntoumanis, 2013) and merit closer examination in the analysis.
- Centred leverage value is a measure of how far away the independent variable values of an observation are from those of the other observations and identifies data points that are exerting undue influence. Values greater than 0.5 indicate outliers (Hahs-Vaughn and Lomax, 2013, p.695).

A number of statistics texts (Hahs-Vaughn and Lomax, 2013, p.133; Field, 2009, p.252) refers to the use of the American Psychological Association (APA) guidelines for the reporting of statistical results. These guidelines (Vandenbos, 2010) recommend particular conventions and formats for reporting results, these recommendations have been used in this research:

- for the reporting of central tendency values, the sample size is denoted as *N*, the symbol *M* is used for the mean and *Mdn* for the median. For normally distributed data, the standard deviation (whose symbol is *SD*) is reported as well as the mean. If the median is being reported, the interquartile range value (*IQR*) is included as well as the Q1 and Q3 values.
- for regression analyses, values are reported in a specific format:

  ($R^2$, F value (*F*), degrees of freedom (*df*) of regression and residual; the significance level, *p*),

  where:

  - $R^2$ is the correlation coefficient squared. It represents the proportion of variance in the outcome that may be statistically explained by the explanatory variables. It is represented as a proportion between 0 and 1, with 0 indicating that the model does not explain any of the variation in the outcome and 1 indicating that it predicts the outcome perfectly. An $R^2$ of 0.5 suggests that the model can explain 50% of the variability in the outcome. Another important parameter is the 'Adjusted $R^2$' which is a measure of the loss of predictive power or shrinkage in regression (Field, 2009, p.781) and is a modified version of $R^2$ that has been adjusted for the number of predictors in the model. The adjusted $R^2$ increases only if the new term improves the model more than would be expected by chance. It decreases when a predictor improves the model by less than expected by chance
  - The F-value statistic tests the overall significance of the regression model by testing the full model against a model with no variables and with the estimate of the dependent variable being the mean of the values of the dependent variable. The F-value is the ratio of the mean regression sum of squares divided by the mean error sum of squares and its value ranges from zero to an arbitrarily large number.

- degrees of freedom (*df*) corresponds to the number of coefficients estimated, minus 1.
- $p$ denotes the statistical significance of each of the independent variables and tests whether the standardised coefficients are equal to 0 in the population. If $p < 0.05$, it can be concluded that the coefficients are statistically significantly different to 0.

For each independent variable in a regression, the unstandardised and standardised regression coefficients, and significance values are reported.

## 5.0 Bridges in the study dataset.

This section describes the study area, the Eirspan bridge management system used to compile the study database and descriptive statistical analyses undertaken on the data.

## 5.1 Characteristics of the study area.

The study area consists of the functional area of Cork County Council and is shown shaded in Figure 5.1.


**Figure 5.1. Study area (Google, 2017).**

The classification of the Irish road network is defined in terms of national, regional and local roads (Government of Ireland, 1993). This categorisation recognises that a road network is required to balance between the demands of mobility and accessibility and thus describes the road network in terms of functionality, with roads arranged into three main groups (Cirillo, 1992; Roess et al, 2004):

- local, whose main function is to provide property access;

- collector, that are intended to provide for both through traffic and property access; and
- arterial, that are primarily for through traffic and with minimal access to property.

Figure 5.2 is a schematic representation of a functionally classified road network and shows local roads providing access to individual properties, collector roads connecting minor settlements and arterial roads connecting cities and towns.

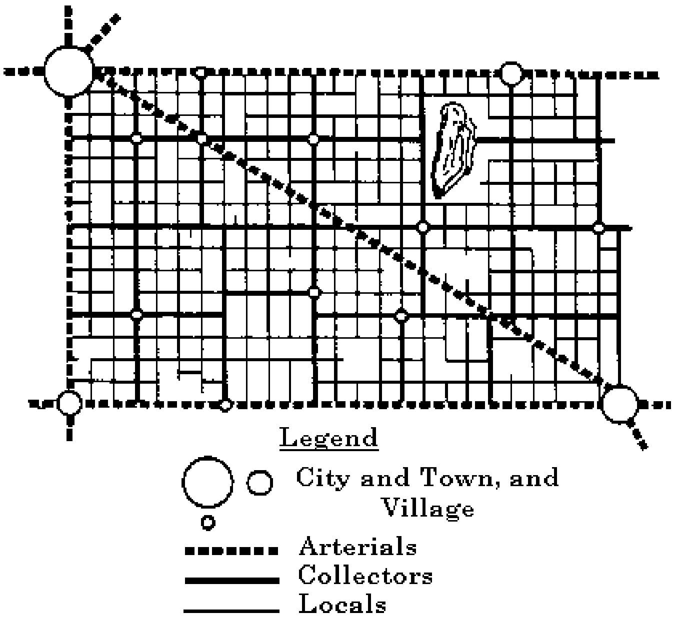



**Figure 5.2. Schematic illustration of a functionally classified road network (FHWA, 2015).**

The national road network is administered by Transport Infrastructure Ireland (formerly the National Roads Authority). This network, which carries 46% of the State's road traffic, is made up of 2,651 km of national primary routes and 2,653 km of national secondary routes, that together amount to just over 5% of all roads (DTTS, 2015b, p.3).

Cork County Council is responsible for the regional and local road network in its administrative area and bridges on this network form the basis of this study. A numbered schedule of these roads is maintained (Cork County Council, 2016) with descriptions published of the functional classification used:

- Regional roads provide the link between national routes and towns and villages which are not located on the busier routes and also provide strategic links between the towns and villages themselves.
- Local primary roads are intended to carry mainly non-HGV (heavy goods vehicles) traffic through rural areas or along link routes between regional roads and towns/villages.
- Local secondary roads make up the link roads between the local primary and regional road network, providing through road access to more rural locations.
- Local tertiary roads are the remainder of the public road network and constitute roads with very low traffic volumes including cul-de-sac roads.

The dataset has bridge structures on all four classifications, with 439 (32%) on regional roads, 454 (33%) on local primary roads, 440 (32%) on local secondary roads and 34 (3%) on local tertiary roads.

Regional and local roads lengths for each of Ireland’s 31 local authorities are presented in Figure 5.3. The study area has 10.7% (1,402 km) of the total length of regional roads (13,120 km) and 13% (10,465 km) of the total length of local roads (84,472 km) in the state. Combining both road classifications, the subject area has 12.7% (11,867 km) of the total road length (93,592 km).

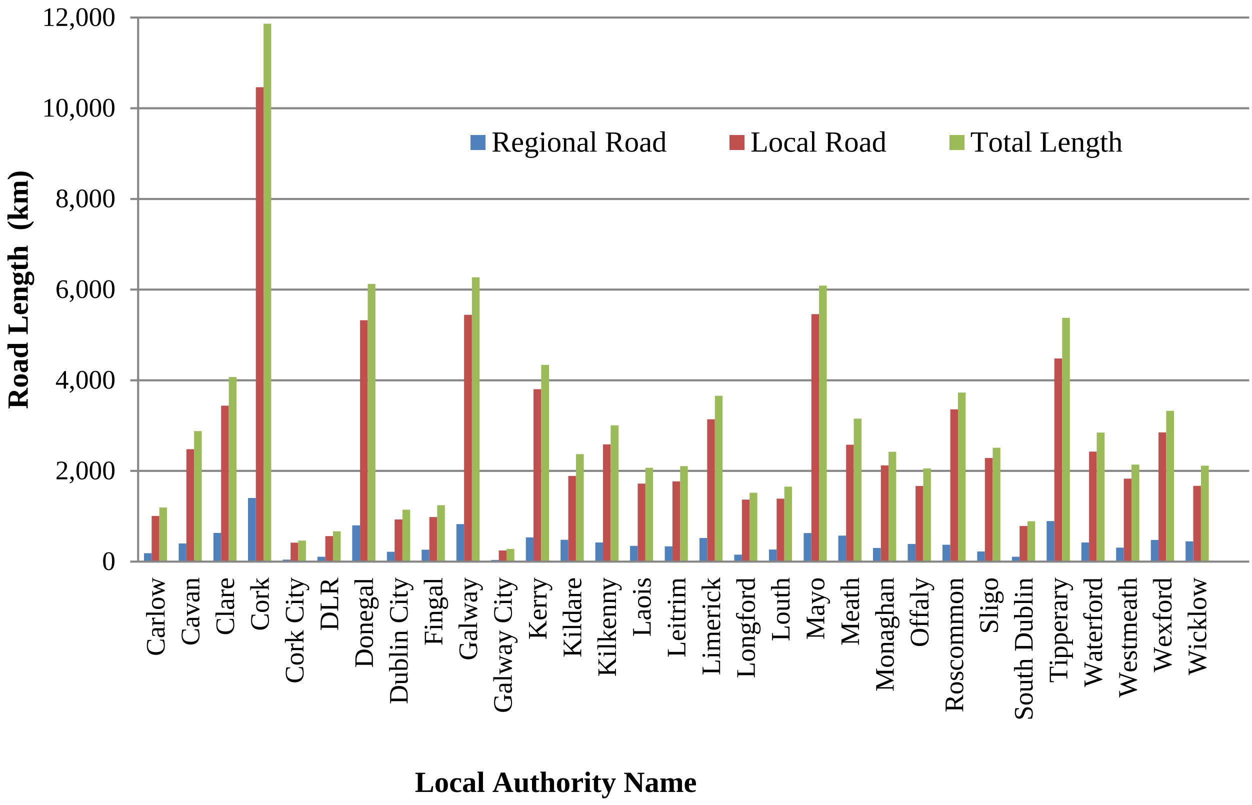



**Figure 5.3. Road lengths by local authority (adapted from Donoghue, 2014).**

The Ordnance Survey of Ireland (OSI, 1958) has published information on Irish rivers and their catchment basins. The catchments are shown in Figure 5.4. The study area is generally drained by three catchments, the Blackwater, Bandon and Lee. These rivers rise at the west of the county and flow in an easterly direction before turning southward and discharging into the Celtic Sea. The remaining rivers outside of these catchments and in the study area flow southward to the sea.

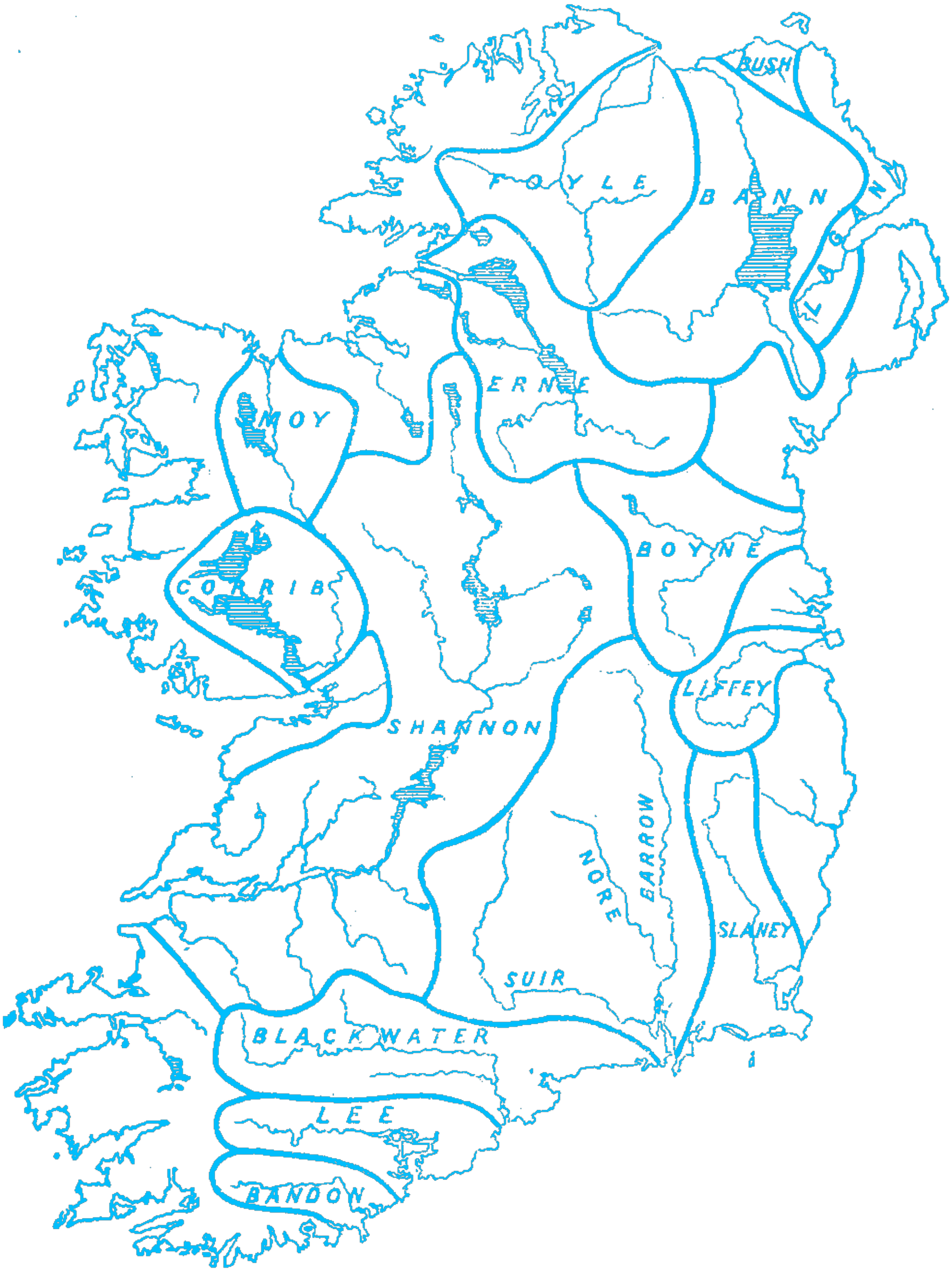



**Figure 5.4. Irish river catchments (OSI, 1958).**

The river lengths in Table 5.1 have been adapted from the OSI data and the river network in the study area has been found to represent 11.8% of the total river length in the State.

**Table 5.1. County Cork river lengths (adapted from OSI, 1958).**

| River name | River length (km) | River name | River length (km) |
|---|---|---|---|
| River Blackwater | 168.20 | Glashaboy River | 24.00 |
| River Owentaraglen* | 27.76 | River Lee | 89.30 |
| River Allow* | 36.61 | River Sullane** | 36.20 |
| River Funshion* | 55.92 | Shournagh River** | 27.00 |
| River Awbeg* | 51.10 | River Bride** | 34.00 |
| River Dalua* | 24.90 | River Bandon | 72.00 |
| River Bride* | 64.00 | River Ilen | 33.39 |
| River Womanagh | 31.00 | Argideen River | 28.57 |
| Owenacurra River | 21.32 | River Owenabue | 33.00 |
| Total length of rivers: 858.27km | | | |

* tributary of River Blackwater

**tributary of River Lee

The Department of Transport, Tourism and Sport (DTTS, 2014a) estimates that there are approximately 19,000 bridges on the State's regional and local road network. This research, with a database of 1,367 bridges, thus has records of 7.2% of the State's estimated regional and local road bridges.

It is reasonable to state that the study area and the available dataset is of national significance, given their relative percentage share of the State's regional and local road lengths, river lengths and number of regional and local road bridges.

## 5.2 Eirspan bridge management system.

In 2001 the National Roads Authority began the introduction of, Eirspan, initially for bridges on national roads (Duffy, 2004) and from 2012, for bridges on regional and local roads. The Eirspan Inventory and Principal Inspection procedures are described in the National Roads Authority manuals (NRA, 2008a, 2008b) and consist of two distinct survey stages:

- bridge inventory collection where the name, location, type and geometry of the bridge stock are recorded and collated. For each structure, up to 58 separate parameters are recorded.
- principal inspection where the damage type is recorded and a condition rating value is assigned to the constituent components and the overall bridge structure. For each structure, up to 21 separate parameters are recorded.

Eirspan describes each structure in terms of 13 individual bridge components, shown in Table 5.2.

**Table 5.2. Bridge components and description (NRA, 2008a).**

| No. | Name | Description |
|---|---|---|
| 1 | Bridge surface | Surfaces on the bridge and on the approaches. |
| 2 | Expansion joints | All expansion joint construction components |
| 3 | Footway / median | Surfaces and kerbs on footways and medians. |
| 4 | Parapet / safety barrier | The parapets, safety barriers and railings at bridge edges and in medians. |
| 5 | Embankment / revetments | Slopes, including slope protection (revetments), adjacent to the abutments and wingwalls. |
| 6 | Wingwalls/ spandrel walls/ retaining walls | Wingwalls and retaining walls which form part of the bridge. |
| 7 | Abutments* | The whole abutment structure including ballast wall, curtain wall, bearing shelf, and visible parts of footings. |
| 8 | Piers* | The whole pier structure including bearing pedestals and visible parts of footings. |
| 9 | Bearings* | Bearings on abutments and piers and in cantilevered superstructures. |
| 10 | Deck / slab* | The part of the superstructure other than beams/girders. |
| 11 | Beams/girders/ transverse beams* | Main beams, cross beams and diaphragms, bracing beams and other similar elements. |
| 12 | Riverbed | The riverbed under, upstream and downstream of a bridge. |
| 13 | Other elements | Any significant components present but not included in the standard components. |

* Critical components

The 'condition rating' system for the individual components is assigned by the trained bridge inspector and is a six point system (ranging from '0' to '5') defined in Table 5.3. These ratings provide a numerical representation of the overall structural condition relative to the original condition. The condition rating of the overall structure is determined by the highest rating of the five 'critical' components (abutments, piers, bearings, deck/slab and beams/girders/transverse beams) shown in Figure 5.5.

**Table 5.3. Eirspan condition ratings (NRA, 2008b).**

| Condition Rating | Definition |
|---|---|
| 0 | No or insignificant damage. |
| 1 | Minor damage but no need of repair. |
| 2 | Some damage, repair needed. |
| 3 | Significant damage. |
| 4 | Damage is critical. |
| 5 | Ultimate damage. |

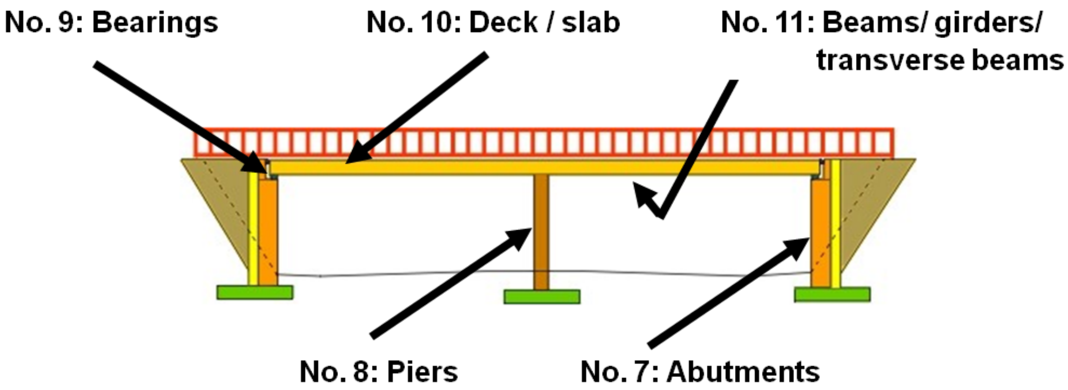



**Figure 5.5. Eirspan critical components.**

The survey data are input into the Eirspan database system and a cost model within the software provides an estimation of rehabilitation costs. A typical Eirspan report has been included in Appendix B.

## 5.3 Dataset consolidation.

From 2012 to 2014, Cork County Council carried out 1,367 inspections to the Eirspan BMS standard on all regional and on strategic local road bridges. The exact number of bridges on the local road network is unknown and not all bridges were inspected.

The dataset of the 1,367 bridge survey observations has been generated by the Eirspan BMS in ‘Notepad’ format. Notepad is a plain text (i.e. data) editor for Microsoft Windows and is a basic text editing program that enables the creation of documents. The Notepad data files were imported in a comma-separated value (CSV) format into Microsoft Excel (which is a computer application for the organisation, analysis and storage of data in tabular format) and converted into a spreadsheet format, where these data were sorted and checked for errors and inconsistencies. The dataset, now in spreadsheet format, can be manipulated and analysed.

## 5.4 Descriptive statistical analyses of the dataset.

Of the surveyed bridges, 1,244 (91%) have three spans or less as shown in Figure 5.6.

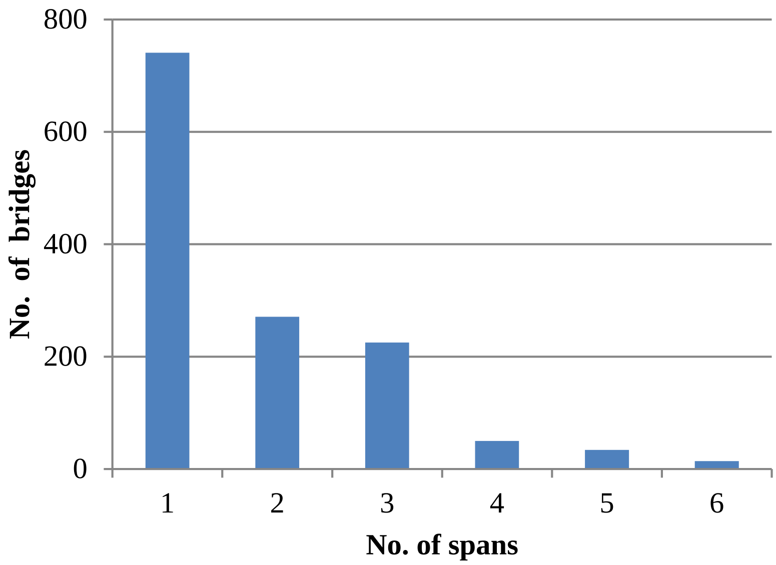



**Figure 5.6. Number of spans of surveyed bridges.**

With respect to span lengths, 1,094 (80%) of bridges have span lengths no greater than 6m as shown in Figure 5.7. To establish a central tendency value for the maximum span length for each bridge shown in Figure 5.7, normality testing was undertaken using SPSS on these data, with missing data values excluded ($N$ =1,333). A Kolmogorov-Smirnov test ($K$-$S$ = 0.843, $df$ = 1,333, $p$ = 0.000) and a visual inspection of their histogram, normal Q-Q plot and box plot showed that these data, with a skewness of 2.269 (SE = 0.067) and a kurtosis of 10.629 (SE = 0.134), are not normally distributed. The median (*Mdn*) value of 3.34m is taken as the measure of central tendency. The interquartile range (*IQR*) is 2.8m, with (Q1, Q3) being (2.3m, 5.1m).

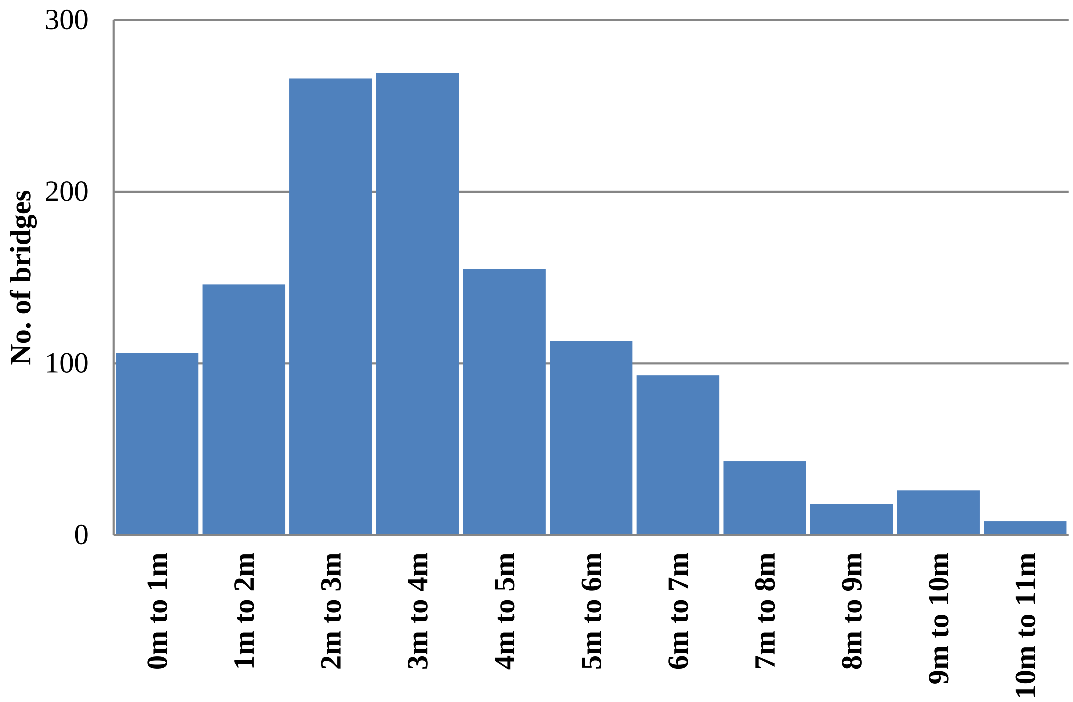



**Figure 5.7. Range of span lengths of surveyed bridges.**

The Eirspan parameter ‘design of elevation of superstructure’ describes the elevation, or longitudinal layout, of the superstructure. The most common type of superstructure elevation comprises the 827 (60.5%) ‘arches of one or more span’ bridges,  followed by the 410 (30% ) ‘simple span, constant cross-section’ bridges as shown in Figure 5.8. In the case of arches, 783 (94.7%) are of stone masonry while for simple spans of constant cross-section, 223 (54.4%) are of in-situ reinforced concrete and 97 (23.7%) are of stone masonry This masonry material may be explained by the presence of ‘clapper’ bridges, which are large flat stone slabs supported on piers and abutments. In the dataset, these bridges have a span range between 0.5m to 2.1m, with an average span of 0.9m. Figure 5.9 shows a typical ‘clapper’ bridge arrangement of four spans, with the large masonry slabs supported by masonry abutments and piers.

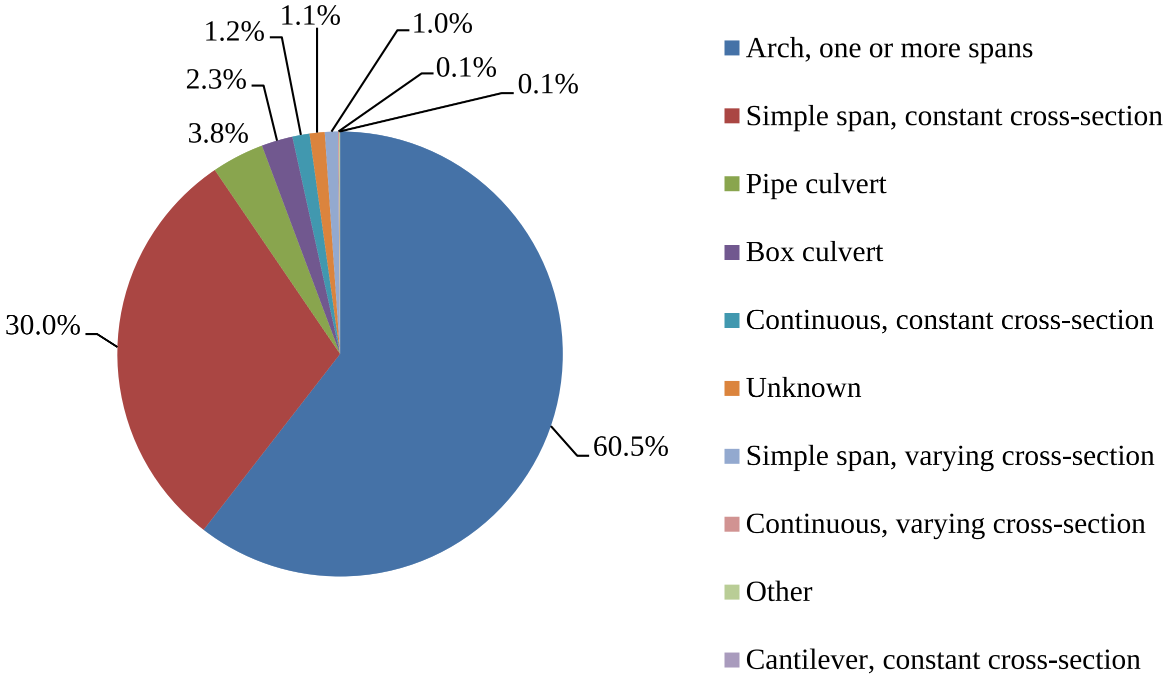



**Figure 5.8. Design of elevation of superstructure.**

**Figure 5.9. Typical ‘clapper’ bridge arrangement (Atkins, 2017).**

From an analysis of the dataset, the percentages of bridges in terms of overall condition rating have been calculated and presented in Figure 5.10. In descending order, 732 (53.5%) are rated condition 2, 272 (19.9%) rated condition 3, 181 (13.2%) rated condition 1, 81 (5.9%) rated condition 4, 34 (2.5%) rated condition 0 and 30 (2.2%) rated condition 5 structures. It may be further noted that 81.5% of the bridges (ratings 2 to 5) have suffered at least some damage while 28% (ratings 3 to 5) have suffered at least significant damage.

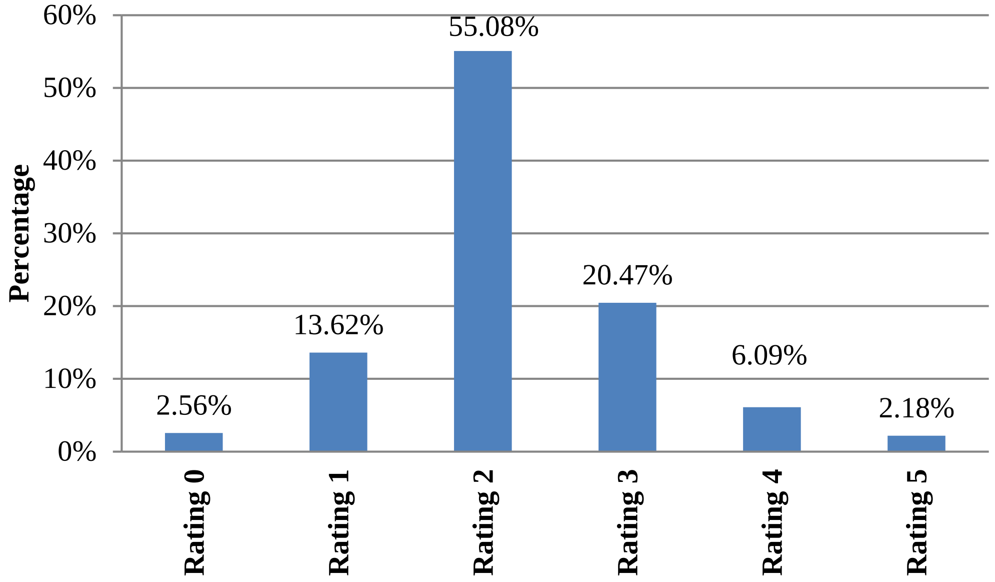



**Figure 5.10. Overall structure ratings of bridge stock.**

Examples of component condition ratings from the dataset are shown in Figures 5.11 to 5.14 and described in Table 5.4.


**Figure 5.11. Pier component rated condition '5' in a structure with an overall condition rating of '5'.**

**Figure 5.12. Intermediate pier component rated condition '5' in a structure with an overall**

**Figure 5.13. Deck/ slab component rated condition '4' in a structure with an overall**

**Figure 5.14. Beams/girders/transverse beams component rated condition '5' in a structure**

**Table 5.4. Comments on examples of component and overall structure condition ratings from the dataset.**

| Figure No | Component and condition rating (CR) | Overall structure condition rating (CR) | Comment |
|---|---|---|---|
| 5.11 | Pier component<br>CR: 5 | CR: 5 | Extensive scour of masonry arch bridge pier, with scour hole extending up to 1m behind face of pier. Cracks and missing masonry from pier. Critical component rating of CR 5 ('ultimate damage'). |
| 5.12 | Pier component<br>CR: 5 | CR: 5 | Extensive scour of intermediate pier has led to partial collapse of pier, with separation from bridge deck. Critical component rating of CR 5 ('ultimate damage'). |
| 5.13 | Deck/ slab component<br>CR: 4 | CR: 4 | Cracking of reinforced concrete bridge deck, with cracks up to 10mm evident and steel reinforcement evident. Critical component rating of CR 4 ('damage is critical'). |
| 5.14 | Beams/girders/transverse beams<br>CR: 5 | CR: 4 | Deterioration of structural steel beams supporting reinforced concrete bridge deck. Some sections of bottom flanges of beams seriously corroded. Critical component rating of CR 5 ('ultimate damage'). |

In the consideration of damage types or defects within systems or processes, Montgomery (2009, p.40) describes the Pareto analysis methodology, which identifies quality issues by category or by type of defect or nonconformity. A Pareto analysis is a quality control technique which assumes that 80% of the quality issues of an end product or service are caused by 20% of the problems in the production or service processes. Once these problems are identified, the quality issues can be addressed and remedied, thus efficiently improving quality. The benefit of a Pareto analysis is the efficient solution of a problem by the identification and the prioritisation of the main causes of the faults, according to their importance.

From the recorded bridge data, the damage types for each critical component have been analysed and presented in a series of Pareto charts, which are frequency distributions of attribute data arranged by category, for the critical components (with the exception of the 'bearings' component, for which there are no records) in Figures 5.15 to 5.18.

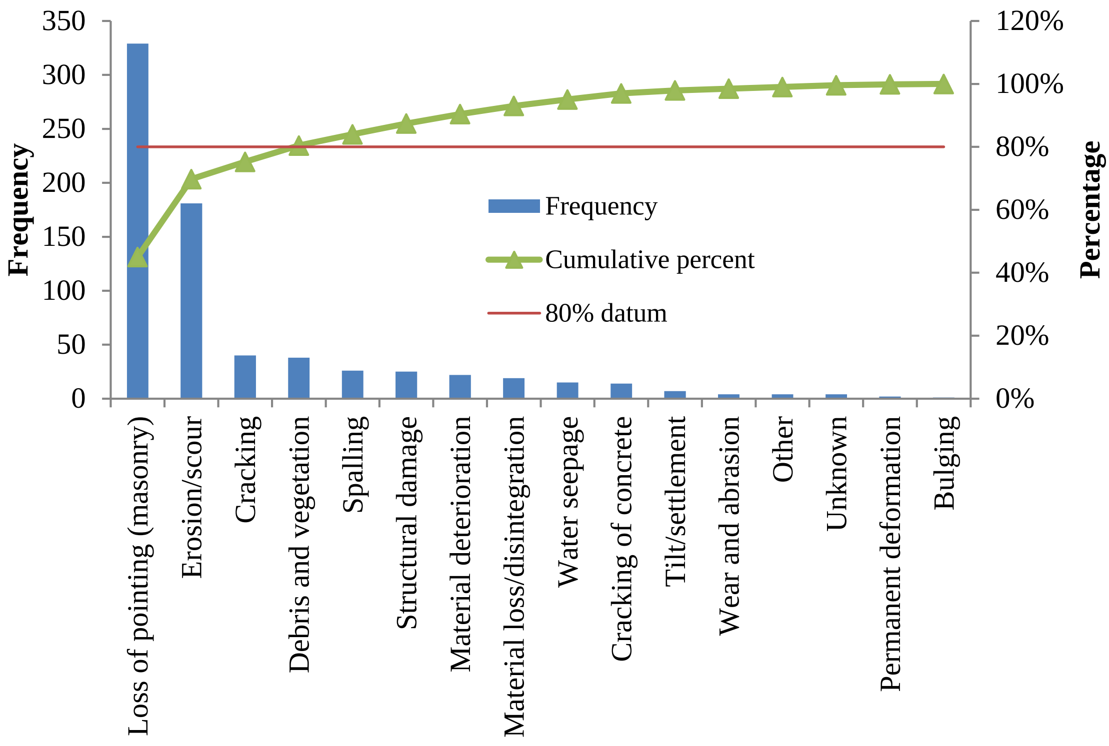



**Figure 5.15. Pareto chart for damage to abutments.**

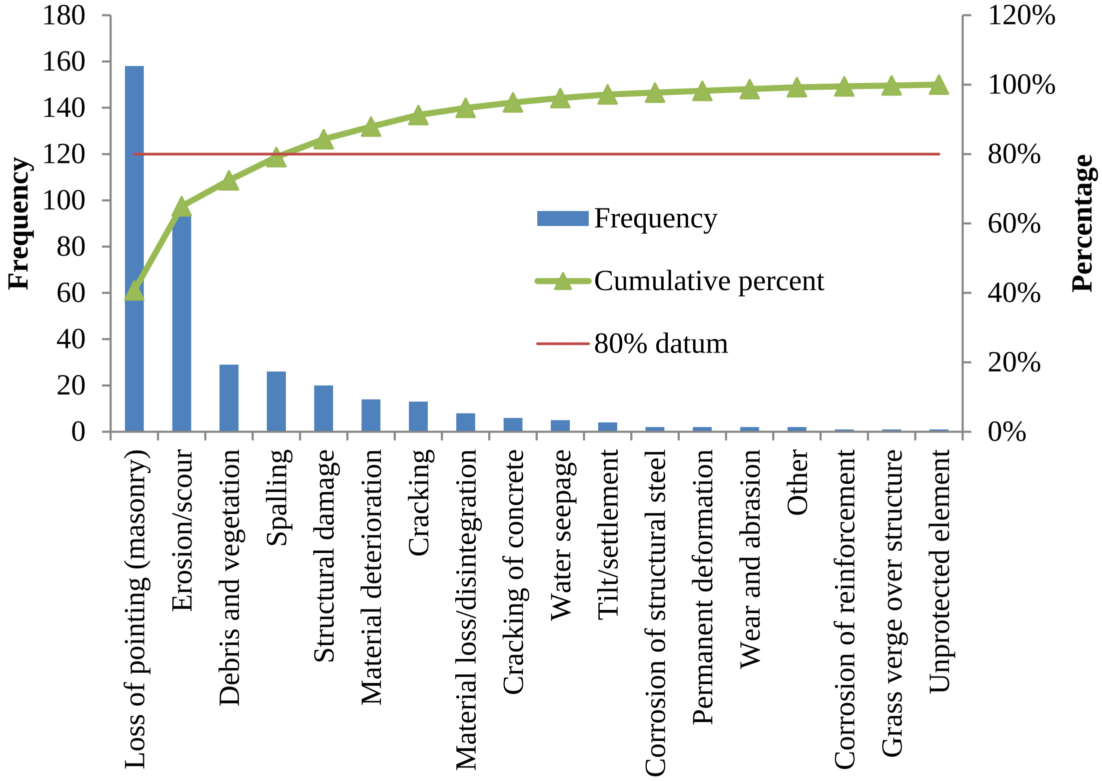



**Figure 5.16. Pareto chart for damage to piers.**

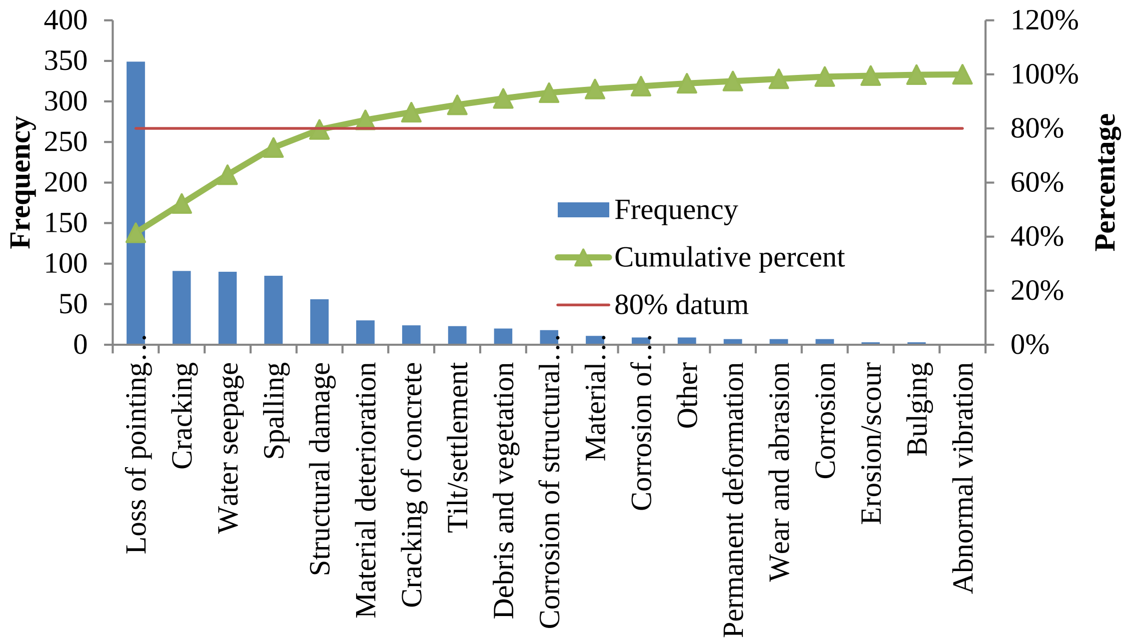



**Figure 5.17. Pareto chart for damage to deck/slab**

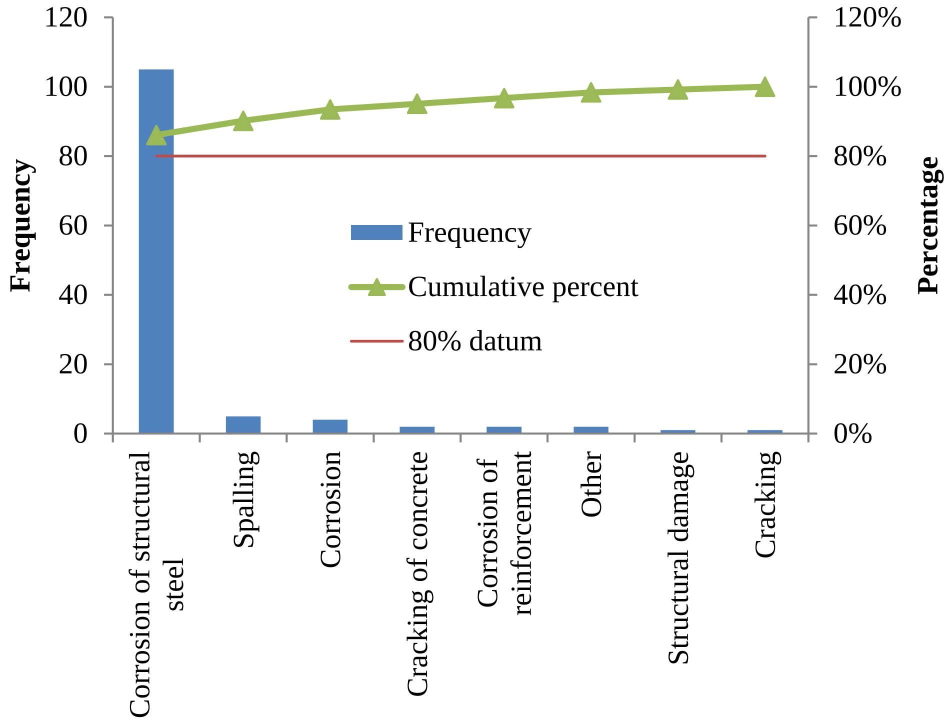



**Figure 5.18. Pareto chart for damage to beams/girders/transverse beams.**

Consideration of Figures 5.15 to 5.18 provides an insight into the main damage types (i.e. those that comprise 80% of the defects):

- for damage to the abutments component (Figure 5.15), the main damage types are loss of pointing, erosion/scour, cracking and debris and vegetation,
- for damage to the pier component (Figure 5.16), the main damage types are loss of pointing, erosion/scour, debris and vegetation and spalling,
- for damage to the deck/slab component (Figure 5.17), the main damage types are loss of pointing, cracking, water seepage, spalling and structural damage,
- for damage to the beams/girders/transverse beams component (Figure 5.18), the main damage type is corrosion of structural steel.

A 'cause-and-effect' or Ishikawa diagram is a visual quality control technique frequently used in determining causes of damage in system analysis (Montgomery, 2009, p.203). The main 'damage types' are consolidated from the individual Pareto analyses and presented graphically in Figure 5.19.

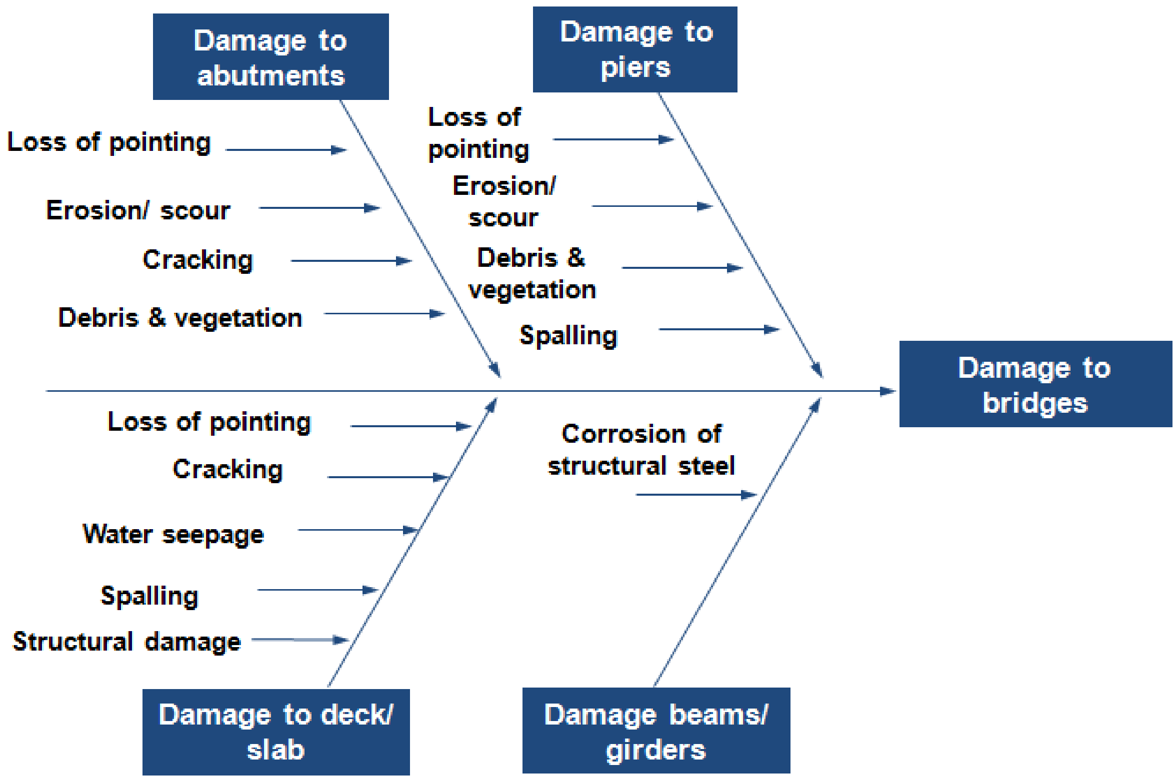



**Figure 5.19. 'Cause and effect' diagram for damage to bridges.**

The high incidence of 'loss of pointing' may be explained by the high percentage (57.3%) of masonry arch structures in the database. An explanation of the high frequency value of 'erosion/ scour' for abutments and piers is less obvious and further research has been undertaken in the next section.

## 5.5 Bridge scour as a deterioration mechanism in the study dataset.

The incidence of erosion and scour damage in the 37 recent (2014 to 2015) condition 4 and 5 rated rehabilitation projects undertaken by Cork County Council has been investigated and compared with published information on bridge failure generally.

By definition, condition 4 and 5 rated bridges indicate structures at failure (‘ultimate damage’) or close to failure (‘damage is critical’). Of the 37 structures, 17 (46%) are condition 5 rated and 20 (54%) are condition 4 rated. Further consideration of these data reveals that:

- 12 of the 17 (70%) instances of overall condition 5 ratings are attributable to a 5 rating for either the abutment or pier component
- 11 of the 20 (55%) instances of overall condition 4 ratings are attributable to a 4 rating for either the abutment or pier component.
- Combining the conditions 4 and 5 ratings indicates that 23 of the 37 observations (62%) are attributable to damage to either the abutment or pier component.

Damage to both bridge abutments and piers generally results from the action of scour. This is a phenomenon whereby the level of the riverbed becomes eroded due the action of water flow, leading to the exposure of bridge foundations, as shown in Figure 5.20.

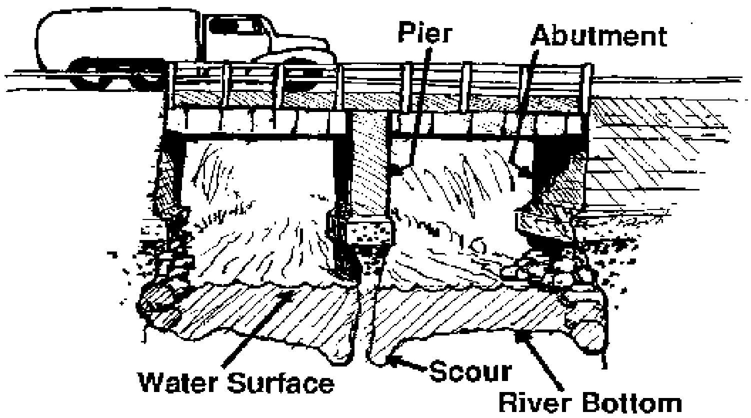



**Figure 5.20. Bridge scour at pier and abutment (Warren, 2016).**

Bridge scour depends on the flow rate, type and condition of the riverbed and the width and depth of the river (Biezma and Schanack, 2007). Kirby et al. (2015) classify scour as either ‘natural’ (associated with the natural variations of flow that occur irrespective of the presence of a structure in a river) or ‘local’ and ‘contraction’ (both attributable to the presence of a bridge or another structure). This is expanded upon by Julien (2002), who describes local scour at bridges in terms of ‘abutment scour’ and ‘pier scour’.

The combined 4 and 5 ratings figure of 62% from the sample group is greater than that of other studies on bridge failures:

- Wardhana and Hadipriono (2003) analysed 503 bridge failures throughout the United States between 1989 and 2001and ascertained that 15.51% of the failures were due to scour;
- Biezma and Schanack (2007) undertook research into 350 cases of worldwide bridge collapses in the last 200 years and report that 25% of the failures were due to scour;
- Cook et al. (2013) researched 92 bridge collapses in New York State between 1987 and 2011 and state that 20.65% may be attributed to scour.

It may therefore be inferred that scour is a particular issue in the study area and that only close examination of these data reveals the high incidence of occurrence.

### 5.6 Rehabilitation cost and estimated asset value of bridge stock.

The total cost for the rehabilitation of the bridge stock has been estimated by the Eirspan database at €24.2 million. Full cost information is available for 1,278 bridges and a list of these structures is included in Appendix C. The cost in terms of condition ratings has been presented in Figure 5.21 and to aid interpretation, the numbers of bridges is also plotted. Condition 2 rated bridges at €12.2 million constitute the largest cost followed by condition 3 rated structures at €6.14 million. These two ratings combined thus account for 75.8% of the total liability of the bridge stock.

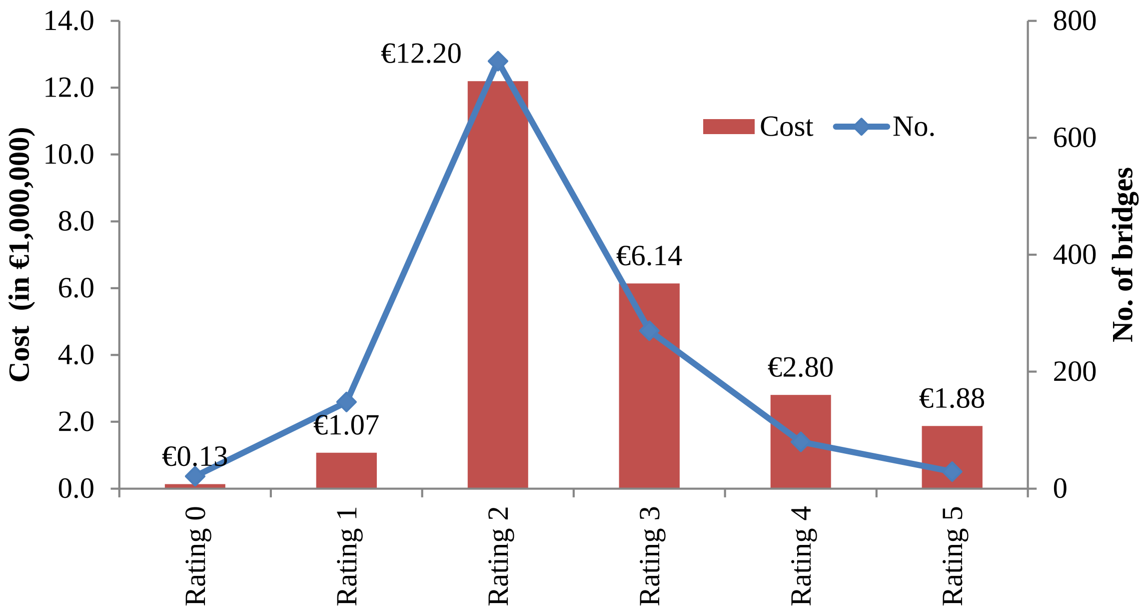



**Figure 5.21. Bridge rehabilitation costs.**

The cost estimate data values were analysed with SPSS software for normality ($p < 0.05$). A review of the Kolmogorov-Smirnov test statistic ($K\text{-}S = 0.252$, $df = 1{,}278$, $p = 0.000$), the skewness statistic of 12.026 ($SE = 0.068$) and the kurtosis statistic of 206.40 ($SE = 0.137$) suggested that the normality assumption was violated. The median (*Mdn*) value of €14,457 is taken as the measure of central tendency. The interquartile range (*IQR*) is €15,437, with (Q1, Q3) being (€7,492, €22,930).

The financial value of a bridge stock may be defined by the cost of replacement of all the constituent bridges (Orcesi and Cremona, 2011; Horak et al., 2001). A review of recent cost estimates for Irish bridge construction projects is shown in Table 5.5, with the costs being reported in terms of bridge deck area.

**Table 5.5 Estimated costs for bridge replacements.**

| Author (Date) | Description of structure | Location | Cost per m² of bridge deck (€/m²) |
|---|---|---|---|
| O'Donovan et al. (2003, p.30) | Prestressed concrete cable-stayed road bridge | Taney Bridge, Dundrum, Co. Dublin | 4,500 |
| RPS (2006a, p.36) | Multi-span in-situ/ precast concrete hybrid road bridge | Shannon Bridge Crossing, Co. Clare | 2,500 |
| RPS (2006b, p.3) | Precast concrete beam road bridge | North Ring Road, Cork | 1,400 |
| URS (2012, p.11) | Lattice steel truss pedestrian bridge | Kilkenny City | 2,400 |
| JBA Consulting (2016, Appendix B-3) | In-situ concrete road bridge | Clifden, Co. Galway | 3,665 |
| RPS (2017, Appendix G) | Arched steel truss pedestrian bridge | Grange, Cork City | 4,000 |

The cost estimates vary with the complexity and site specific issues of individual projects. Given that the bridges of this study have been shown to be generally of short span (80% have span lengths no greater than 6m), it is reasonable to infer that replacements would be at the lower end of the cost estimates of Table 5.4. A cost of €2,500 per square metre of bridge deck could be assumed to reflect the likely replacement costs.

Examination of the database yields a value of 81,676 $m^2$ as the total bridge deck area. Applying a cost of €2,500 /$m^2$, gives the bridge stock an asset value of €204,190,000.

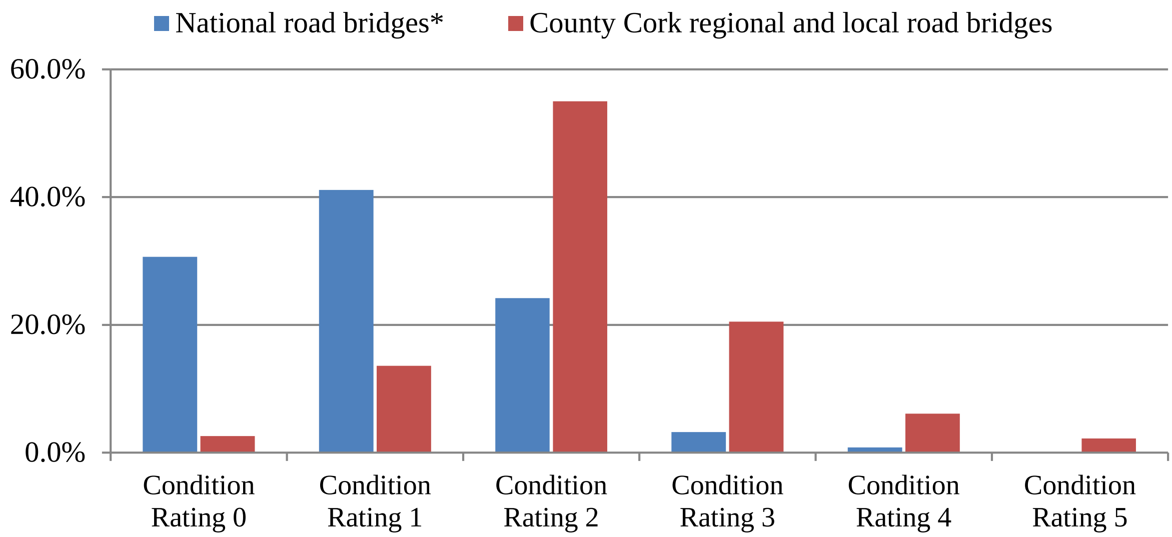
## 5.7 Comparison with the bridge stock on national roads.

The Department of Transport, Tourism and Sport (DTTS, 2015b) has published data on the material type and overall condition ratings of the 2,575 bridges on national roads in 2012. This record allows a comparison of a contemporaneous dataset with the County Cork regional and local road bridges of this study. Table 5.6 compares the bridge stock in terms of material type and Figure 5.22 compares overall condition ratings.

**Table 5.6 Comparison of national road and study area bridge material types.**

| Bridge material type | National road bridges* (%) | County Cork regional and local road bridges (%) |
|---|---|---|
| Concrete | 59.0 | 33.8 |
| Masonry | 27.0 | 65.3 |
| Steel | 9.0 | 0.2 |
| Other | 5.0 | 0.7 |

*(adapted from DTTS, 2015b, p.110)




*(adapted from DTTS, 2015b, p.112)

**Figure 5.22 Comparison of 2012 national road and study area overall bridge condition ratings.**

There is a marked difference in terms of material type between the national road bridge stock and the County Cork stock:

- 59% of the national road bridges are concrete structures compared to 33.8% of the County Cork stock;
- 65.3% of the County Cork stock are masonry structures compared to 27% of national road bridges;
- 9% of the national road bridges are steel structures compared to 0.2% of the County Cork stock.

The condition rating comparison indicates that the national road bridges are generally in better condition than the subject bridges of this study:

- 28.2% of the national road bridges have suffered at least some damage (condition ratings 2 to 5), while 4% have significant damage (condition ratings 3 to 5);
- 83.8% of the regional and local road bridges in the study area have at least some damage (condition ratings 2 to 5), while 28% have significant damage (condition ratings 3 to 5);
- 71.8% of the national road bridges have no or insignificant damage compared to 16.2% of the regional and local road bridges.

It may therefore be inferred from the comparison that the two bridge stocks differ considerably in terms of material type and overall condition ratings. It can reasonably be assumed that the national bridge stock has benefited from the construction of national roads in recent decades, resulting in new bridge structures.

## 5.8 Recent bridge rehabilitation projects in the study area.

A bridge structure will deteriorate over time to an unacceptable performance level if no maintenance is carried out. Figure 5.23 shows the consequences of undertaking no maintenance which will ultimately lead to the requirement for replacement, while both preventative and corrective maintenance actions extend the time where a structure will provide the minimum acceptable performance.

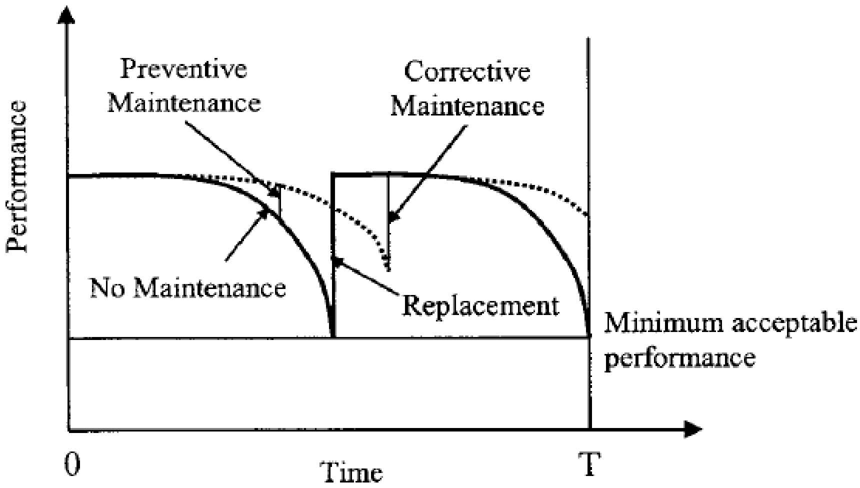



**Figure 5.23. Bridge performance vs. time (Morcous, 2006)**

Annual investments in bridge rehabilitation for the period 2014 to 2017 are shown in Table 5.7. The average annual value of investment over the period was €869,904, which represents 0.43% of the bridge stock asset value of €204,190,000. There was an average of 20 projects per annum.

**Table 5.7. Bridge investment in the study area 2014-2017.**

| Author/ Year | Grant (€) | No. of bridge rehabilitation projects (no.) |
|---|---|---|
| DTTS (2014b) | 737,855 | 23 |
| DTTS (2015a) | 862,254 | 19 |
| DTTS (2016) | 866,291 | 18 |
| DTTS (2017) | 1,013,216 | 20 |

Recent rehabilitations have generally been the repair of masonry structures and the replacement of failed structures with precast concrete culverts. The methodologies in the repair of masonry bridges have been reported by Darby et al. (2000, pp.707-719), Wilmers

(2012) and Garrity (2015). Figures 5.24 to 5.27 show typical sample rehabilitation projects with brief descriptions of the work elements given in Table 5.8.

**Figure 5.24. Before and after photographs of rehabilitation project at R585 Cousane West Bridge.**

**Figure 5.25. Before and after photographs of rehabilitation project at R603 Kilbrittain Bridge.**

Figure 5.26. Before and after photographs of rehabilitation project at L7231 Kildarra Bridge.

Figure 5.27. Before and after photographs of rehabilitation project at L6982 Transtown North Bridge.

**Table 5.8. Bridge rehabilitation projects in the study area.**

| Bridge Name | Structural issue | Condition Rating before works | Rehabilitation technique | Condition Rating after works |
|---|---|---|---|---|
| R585 Cousane West Bridge | Scouring of abutments and floor. Loss of pointing in spandrel wall. | CR: 4 | Reconstruction of abutments. Replacement of bridge floor with a concrete slab. Re-pointing of masonry walls and arch barrel. | CR: 0 |
| R603 Kilbrittain Bridge | Scouring of abutments, piers and floor. Bulging of spandrel walls. | CR: 4 | Reconstruction of abutments and piers. Replacement of bridge floor with a concrete slab. Reconstruction of parapet walls. Re-pointing of masonry walls and arch barrels. Placement of lateral ties and “pattress” anchorage plates. | CR: 0 |
| L7231 Kildarra Bridge | Scouring of abutments and floor. Bulging of spandrel walls. Collapse of section of spandrel wall. | CR: 5 | Reconstruction of abutments and piers. Replacement of bridge floor with a concrete slab. Re-pointing of masonry walls and arch barrels. Reconstruction of parapet walls. Placement of lateral ties and “pattress” anchorage plates. | CR: 0 |
| L6982 Transtown North Bridge | Failure of 2 span masonry arch structure. | CR: 5 | Replacement of the structure with a precast concrete “box” culvert. | CR: 0 |

The delivery of rehabilitation construction projects faces a number of challenges (M. O’Sullivan, 2016, personal communication, 17 October):

- the requirement for statutory approvals. The consent of the Office of Public Works (OPW) is required for the construction, replacement or alteration of bridges and culverts (OPW, 2013);

- environmental constraints. Depending on the particular river, the requirements of Inland Fisheries Ireland (IFI) may constrain the length of time to undertake in-stream works to the period July to September (IFI, 2016); and
- lack of capacity in a specialised sector of the construction industry. Bridge rehabilitation projects require contractors with specialised technical knowledge and capabilities. AECOM (2016, p.7), in a review of the Irish construction industry, point to a lack of capacity generally and in specialised sectors in particular.

## 6.0 Deterioration model for bridge structures.

The rate of deterioration predicts the future condition or performance of an asset if no maintenance, rehabilitation or improvements are undertaken. If both the current condition and deterioration rate (or performance curve) are known, as shown in Figure 6.1, the remaining period of time in which the asset satisfies all of its functional requirements may be estimated.

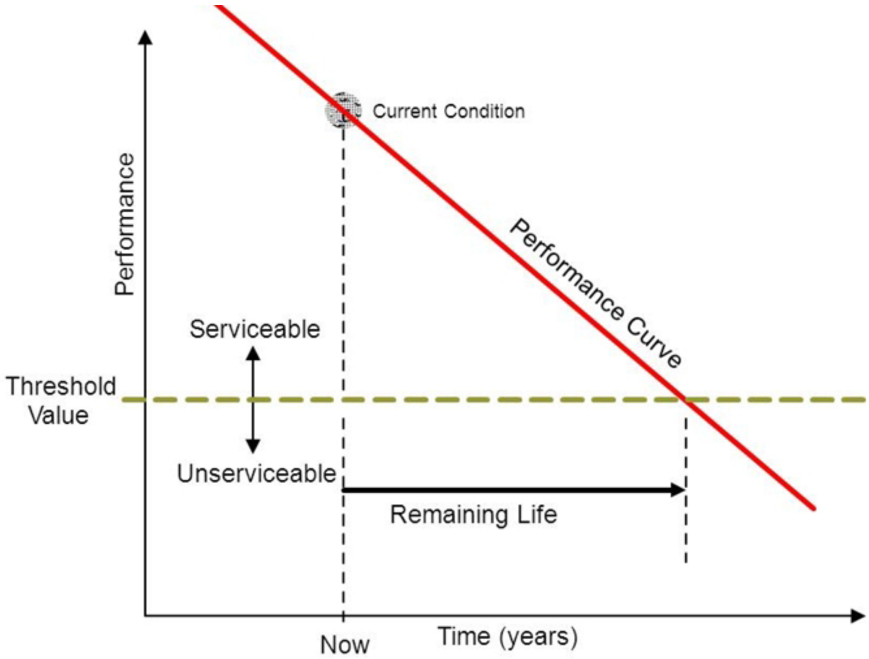



**Figure 6.1. Asset performance vs. time (WERF, 2017).**

This research uses a deterministic model approach where statistical regression is undertaken on published bridge life expectancy values. A literature review has yielded the life expectancy values in Table 6.1. These values were statistically analysed to establish a deterioration model for this research.

To reflect the specific study area, life expectancies with broadly similar bridge stock characteristics from Europe only are considered e.g. the Danish data, which includes masonry structures. These data are converted to the six point Eirspan system condition rating convention and a simple linear regression analysis conducted on the sample of 101 data points to determine if the 'Condition Rating' (the dependent variable) could be predicted from 'Age' scores (the independent variable). The sample was screened for missing data and violation of assumptions prior to analysis. Two models were investigated for violations of assumptions:

- Model 1, where outliers were identified and labelled, and
- Model 2, where identified outliers were removed from the analysis.

**Table 6.1 Bridge life expectancy values.**

| Author, Date | Study area | Years |
|---|---|---|
| OECD, 1992 | Denmark | 76 |
| | Finland | 86 |
| | Japan | 43 |
| | Sweden | 73 |
| | Switzerland | 95 |
| | UK | 61 |
| Gion et al., 1993 | Indiana, USA | 57 |
| van Noortwijk and Klatter, 2004 | Netherlands | 90 |
| MIIC, 2005 | Massachusetts, USA | 60 |
| Hearn and Xi, 2007 | Colorado, USA | 56 |
| Caner et al., 2008 | Turkey | 80 |

1. **Model 1.**
   a) **Linearity:** The scatterplot of the independent variable (Age) and the dependent variable, Condition Rating (CR), indicated that the assumption of linearity is reasonable i.e. as Age increases, CR scores also increase.

b) **Independence:** The Durbin–Watson statistic, which tests for serial correlations between errors, was computed to evaluate independence of errors and was 0.247, which is considered acceptable. This suggested that the assumption of independent errors was being met.
c) **Homogeneity of variance**: The presence of two outliers in a scatterplot of the regression standardised residuals against the standardised predicted values for the dependent variable indicated violation of this assumption, based on the -3 to 3 limit values. These data points are identified and labelled.
d) **Normality**: The assumption of normality was tested by examination of the standardised residuals, which for a simple linear regression should be a normal distribution. A review of the Kolmogorov-Smirnov test statistic (*K-S* = 0.889, *df* = 101, *p* = 0.000), the skewness statistic of 1.318 (*SE* = 0.240) and the kurtosis statistic of 1.841 (*SE* = 0.476) suggested that these data are not normally distributed.

Model 1 thus complied with two (linearity and independence) of the four assumptions. The outliers identified were removed and Model 2 assessed.

2. **Model 2.**
   a) **Linearity:** The scatterplot of the independent variable and the dependent variable indicated that the assumption of linearity is reasonable.
   b) **Independence:** The Durbin–Watson statistic calculated was 0.279, which is considered acceptable.
   c) **Homogeneity of variance:** The spread of regression standardised residuals appeared fairly constant over the range of values of the standardised predicted values and provides evidence of the homogeneity of variance.
   d) **Normality:** The assumption of normality was again tested by examination of the standardised residuals. A review of the Kolmogorov-Smirnov test statistic (*K-S* = 0.184, *df* = 99, *p* = 0.000), the skewness statistic of 1.122 (*SE* = 0.243) and the kurtosis statistic of 0.973 (*SE* = 0.481) suggested that these data are not normally

distributed. The literature, however, raises some doubt as to the requirement for compliance with the normality assumption. Gelman and Hill (2006, p.46) and Wheeler (2013) write that the least important regression assumption is that the residuals are normally distributed. Lumley et al. (2002) state that the t-test and least squares linear regression do not require any assumption of normal distribution of the residuals in sufficiently large samples, and refers to previous simulation studies showing that “sufficiently large” is often under 100. The aim of this research is to estimate the regression coefficients and generate predictions in such a way as to minimise mean squared error. In that context, the normality assumption is ignored for this work and compliance with the remaining three assumptions deemed adequate.

Having accepted compliance with the assumptions, a simple linear regression was calculated by the direct method to predict condition ratings using the Eirspan six-point scale convention of bridge structures, based on their age in years. The analysis results from both models 1 and 2 are shown in Table 6.2. A significant regression equation was found ($R^2$ = 0.949, F(1,97) = 1818.75, p < 0.001). The derived regression equation is:

$$\textbf{Condition rating} = \mathbf{0.160 + 0.057\ (Age)} \qquad \mathbf{(14)}$$

where condition rating is measured on the Eirspan scale and Age is measured in years. The bridge condition rating value increases by 0.057 every year i.e. there is a one point increase in condition rating every 17.5 years. The adjusted $R^2$ value indicated that approximately 95% of the variation in ‘Condition Rating’ scores was predicted by the ‘Age’ scores.

**Table 6.2 Model 1 and 2 simple linear regression analysis results.**

| Variable | Model 1 | | Model 2 | |
|---|---|---|---|---|
| | Unstandardised Coefficient | Standardised Coefficient | Unstandardised Coefficient | Standardised Coefficient |
| Intercept | 0.161** | | 0.160** | |
| Age | 0.056* | 0.974 | 0.057* | 0.968 |
| *N* | 101 | | 99 | |
| F-statistic | 1478.38 | | 1818.75 | |
| $R^2$ | 0.937 | | 0.949 | |
| Adjusted $R^2$ | 0.937 | | 0.949 | |

$^{*}p < 0.001$, $^{**}p < 0.05$

Figure 6.2 plots the derived regression equation, which forecasts a bridge lifespan of 85 years, with the European sample data, which has a minimum lifespan value of 61 years for the UK and a maximum lifespan of 95 years for Switzerland.

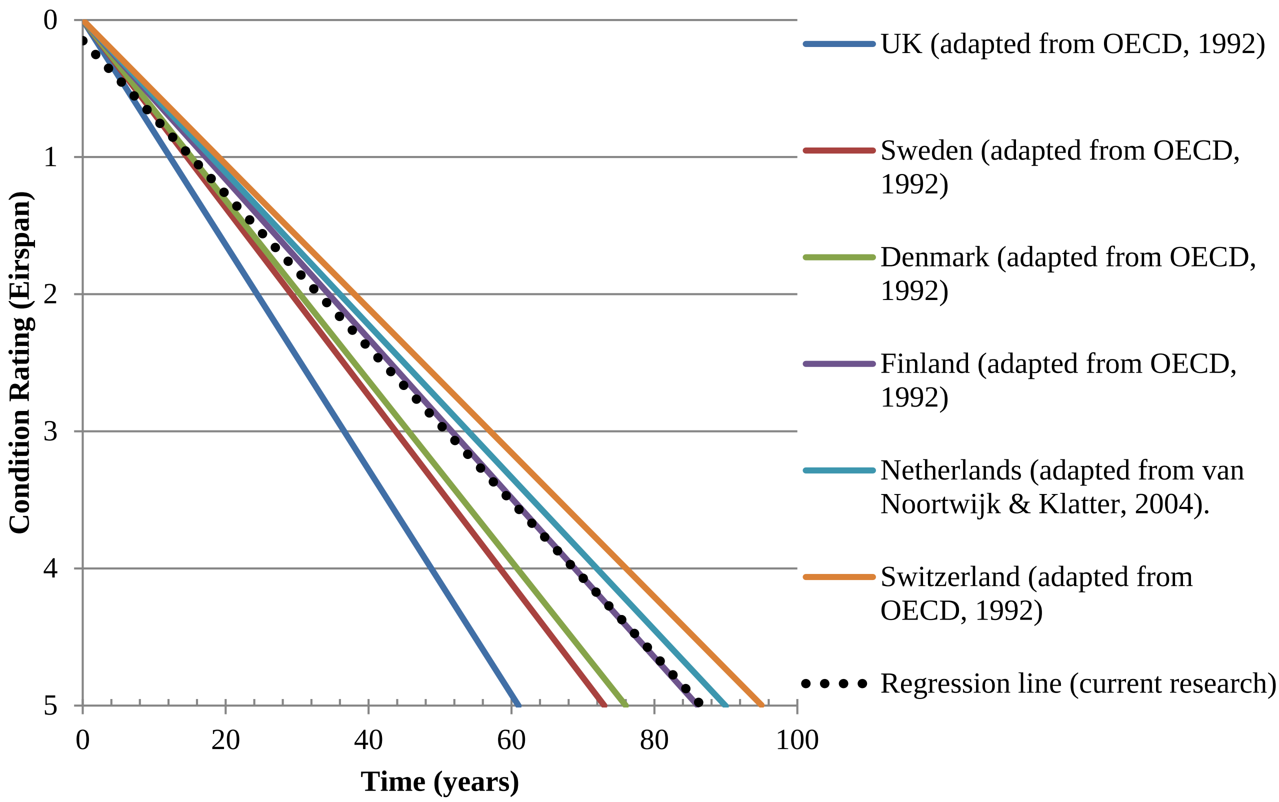



**Figure 6.2 Regression analysis of European bridge life expectancy values.**

## 7.0 Prioritisation model for bridge rehabilitation projects.

An objective of this research is the development of a project priority index to enable the ranking or sequencing of rehabilitation projects that will in turn inform the funding requirements and ultimately, the overall strategy. This Section reviews a previous research methodology and proposes a process based on the available dataset and record of recent rehabilitation projects.

### 7.1 Previous research.

This work takes as a basis the research of Valenzuela et al. (2010), who proposed an integrated bridge index (IBI) for bridges on the Chilean road network by the consideration of influencing factors and from the statistical analysis of surveys of experts. This index takes the form:

$$\mathbf{IBI = -\,1.411 + 1.299BCI + 0.754HV + 0.458SR - 0.387SI} \qquad \mathbf{(15)}$$

where:

- BCI is the bridge condition index that represents the structural damage level according to the distresses observed by visual inspection,
- HV is the hydraulic vulnerability index and is based on visual inspection,
- SR is the seismic risk index and is estimated based on the likelihood of damage,
- SI reflects the importance of the bridge in the road network and is calculated as:

$$\mathbf{SI = 0.261EA + 0.206T + 0.193SEE + 0.093W + 0.133L + 0.114R} \qquad \mathbf{(16)}$$

where:

- EA is the alternative route index,
- T is the average annual daily traffic (AADT) index,
- SEE is the social and economic environment index,

- W and L are the bridge length and width indices,
- R is the load restriction index.

The authors undertook a case study using the IBI on a set of six bridges in Chile and the application of the formula yielded a ranked prioritised list of maintenance projects. The authors concluded their research by stating that further investigation into the inclusion of maintenance costs in the index is required.

### 7.2 Proposed methodology for the formulation of a prioritisation index.

This research proposes a prioritisation index based on:

- a survey of expert practitioners in ranking influencing factors for rehabilitation projects,
- a review of recent rehabilitation projects on critical condition 4 and 5 rated structures and the formulation of a priority index based on the statistical analysis of the influencing factors used in ranking these projects,
- the formulation of a priority index for non-critical condition 2 and 3 rated structures by the statistical analysis of a sample of bridge inspection records sorted and ranked by the preferences of the survey of experts, and
- the application of the derived indices to the subject dataset to enable the priority ranking of all structures.

#### 7.2.1 Identification of influencing factors based on a survey of experts.

In a manner similar to Valenzuela et al. (2010), a survey panel of 33 experts was asked to rate in a questionnaire the order of precedence of ten stated influencing factors (the predictor variables). A sample copy of the questionnaire is included in Appendix D. The respondents included road authority engineers experienced in bridge construction and rehabilitation (35%), road authority engineers experienced in road network management

(43%) and consulting engineers experienced in bridge design and rehabilitation (22%). A total of 23 (70%) responses was received.

The ten influencing factors, based on variables informed by the work of Valenzuela et al. (2010) in Chile and Amini et al. (2016) in Iran as impacting upon rehabilitation projects, have been further reduced to a number of intervals with the coding values described in Table 7.1.

**Table 7.1. Influencing factors.**

| Influencing factor | Description | Interval values |
|---|---|---|
| AADT | AADT (Annual Average Daily Traffic) is the total volume of vehicular traffic on a roadway for one year, divided by the number of days in the year | 1. AADT < 1,000<br>2. 1,000 < AADT < 3,000<br>3. 3,000 < AADT < 10,000<br>4. AADT > 10,000 |
| Alternative route | The length of diversion route on to roads of equal capacity, should the structure become unable to cater for traffic. | 1. There exists an alternative route near the bridge. Diversion < 1km<br>2. There exists an alternative route near the bridge. 1km < Diversion < 10km<br>3. Alternative route increases travel time and road user costs. Diversion > 10km<br>4. No diversion route available |
| Design of elevation | The bridge elevation types from the Eirspan database. | 1. Arch, one or more spans<br>2. Continuous, constant cross section<br>3. Simple span, constant cross section<br>4. Simple span, varying cross section |
| Hydraulic vulnerability | The highest recorded value for either abutment or pier component as defined by Eirspan inspection. | 1. No or insignificant damage<br>2. Minor damage but no need of repair<br>3. Some damage, repair needed<br>4. Significant damage<br>5. Damage is critical<br>6. Ultimate damage |

**Table 7.1 (cont'd). Influencing factors.**

| Influencing factor | Description | Interval values |
|---|---|---|
| Overall structural condition | The condition rating of the overall structure as defined by Eirspan inspection. | 1. No or insignificant damage<br>2. Minor damage but no need of repair<br>3. Some damage, repair needed<br>4. Significant damage<br>5. Damage is critical<br>6. Ultimate damage |
| Material of primary members | The bridge material types of the rehabilitation projects from the Eirspan database | 1. Composite steel and concrete<br>2. In-situ reinforced concrete<br>3. Precast reinforced concrete<br>4. Stone masonry |
| Number of spans | Number of spans of the bridge structure | 1. 1-span<br>2. 2-span<br>3. 3-span<br>4. > 3-span |
| Rehabilitation cost | The cost to improve the structure to condition rating 0 | 1. Cost < €20,000<br>2. €20,000 < Cost < €50,000<br>3. €50,000 < Cost < €100,000<br>4. Cost > €100,000 |
| Road classification | The classification of Regional and Local Roads in the study area in terms of functionality | 1. Regional<br>2. Local Primary<br>3. Local Secondary<br>4. Local Tertiary |
| Structural non-scour condition | The highest recorded rating value of the critical components, excluding the abutment and pier components as defined by Eirspan inspection | 1. No or insignificant damage<br>5. Minor damage but no need of repair<br>2. Some damage, repair needed<br>3. Significant damage<br>4. Damage is critical<br>5. Ultimate damage |

The experts were asked to rank the factors in order of importance. The results from each respondent were processed by assigning a value of '10' to the first factor, '9' to the second factor and so on. These survey results were then tested for normality using SPSS software. Shapiro-Wilks tests ($p>0.05$) and a visual inspections of their histogram, normal Q-Q plots and box plots showed that of the ten factors, three (Alternative route, AADT and Overall structural condition) were found to be normally distributed. The remaining seven categories were found to be not normally distributed and, to provide a robust measure of central tendency, the median values were used to rank in order of priority the results obtained from the analysis, which are shown in Table 7.2.

**Table 7.2. Ranked influencing factors from expert survey.**

| Ranking (No.) | Influencing factor | Number of responses (N) | Median cost (Mdn) | Interquartile range (IQR) | Range (Q1, Q3) |
|---|---|---|---|---|---|
| 1. | Overall structural condition | 23 | 10 | 1 | (9, 10) |
| 2. | Hydraulic vulnerability | 23 | 9 | 1 | (8, 9) |
| 3. | Structural non-scour condition | 23 | 8 | 1 | (7, 8) |
| 4. | Average Annual Daily Traffic | 23 | 6 | 2 | (6, 8) |
| 5. | Availability of alternative route | 23 | 6 | 3 | (4, 7) |
| 6. | Rehabilitation cost | 23 | 5 | 2 | (4, 6) |
| 7. | Road classification | 23 | 5 | 3 | (4, 7) |
| 8. | Number of spans | 23 | 3 | 2 | (1, 3) |
| 9. | Bridge material type | 23 | 2 | 1 | (2, 3) |
| 10. | Bridge type | 23 | 2 | 2 | (1, 3) |

### 7.2.2 Prioritisation index for the rehabilitation of critical condition bridges.

The highway authority undertook the rehabilitation of 37 condition 4 (‘Damage is critical’) and 5 (‘Ultimate damage’) rated bridges in 2014 and 2015. These projects were deemed to be the most urgent and received funding priority. Figures 7.1 and 7.2 show two of the bridges before and after rehabilitation. Both of these structures, L2958 Anname Bridge and L5711 Ballybeg Bridge, were severely damaged masonry arch structures and rated as condition ‘5’. As is evident from Figures 7.1 and 7.2, both were vulnerable to hydraulic damage. While both were on local roads, they carried considerable traffic volumes (3,000 AADT <10,000) and alternative diversion routes were not readily available within 10km.


**Figure 7.1. Before and after photographs of rehabilitation project at L2958 Anname Bridge.**


**Figure 7.2. Before and after photographs of rehabilitation project at L5711 Ballybeg Bridge.**

The details of 37 rehabilitation projects in the study area were reviewed and listed in their order of undertaking (priority number). Multiple regression analysis was conducted using SPSS statistical software, with the priority number being the dependent variable and the influencing factors, identified from the expert survey, being the independent variables.

A multiple regression analysis was conducted on the data sample ($n$ = 37) to establish the best combination of independent variables that predict the dependent or predicted variable, the priority number. Stepwise multiple regression was used; in this method, independent variables are entered into the regression equation one at a time based upon statistical criteria. At each step in the analysis, the independent variable that contributes the most to the prediction equation in terms of increasing the multiple correlation (R) is entered first. This process is continued only if additional variables contribute statistically to the regression equation. Thus, not all independent variables may enter the equation in stepwise regression. The sample was screened for violation of assumptions prior to the analysis and two models were investigated:

- Model 1, which was an exploratory model to identify the independent variables that best predicted the dependent variable and where outliers were labelled and identified, and
- Model 2, where identified outliers were removed from the analysis.

**Model 1.**

a) **Sample size:** The sample size ($n$ = 34) was greater than the necessary 30 required for 15 cases of data for each of the two explanatory variables (overall structural condition and AADT) identified as best predicting the dependent variable.

b) **Linearity:** A review of the scatterplots of the dependent variable (priority number) and the two independent variables indicated that linearity was a reasonable assumption.

c) **Normality:** The assumption of normality was tested by examination of the standardised residuals. A review of the Shapiro-Wilk test statistic ($S$-$W$ = 0.932, $df$ = 37, $p$ = 0.026), the skewness statistic of -0. 983 ($SE$ = 0.388) and the kurtosis statistic of 1.457 ($SE$ = 0.759) suggested that the normality assumption was a reasonable assumption.

- **d) Independence:** The Durbin-Watson statistic was computed at 1.251, which was considered acceptable.
- **e) Homogeneity of variance:** The spread of regression standardised residuals appeared constant over the range of values of the standardised predicted values, with the exception of one outlier identified outside the -3 to 3 value range.
- **f) Multicollinearity:** A review of the Pearson correlation matrix indicated that all values were between -0.9 and +0.9. The calculated collinearity statistics indicated that the values of tolerance were above the 0.1 limit and the values of variance inflation factor were less than the 10 value limit. It was reasonable to infer that there was no violation of the multicollinearity assumption.
- **g) Significant outliers, high leverage and highly influential points:**
  - the maximum Mahalanobis distance was calculated as 7.31. By reference to the Chi-square distribution table, with two degrees of freedom and 95% confidence, the maximum value should be 5.99. There were two values above this limit and these were therefore labelled as outliers.
  - the maximum Cook's distance and Central Leverage Value were below the respective 1 and 0.5 limits.

**Model 2.**

- **a) Sample size:** The sample size ($n$ = 31) is greater than the necessary 30 required for 15 cases of data for each of the two explanatory variables identified as best predicting the dependent variable.
- **b) Linearity:** A review of the scatterplots of the dependent variable (priority number) and the two independent variables indicated that linearity was a reasonable assumption.
- **c) Normality:** The assumption of normality was tested by examination of the standardised residuals. A review of the Shapiro-Wilk test statistic ($S$-$W$ = 0.950, $df$ = 34, $p$ = 0.123), the skewness statistic of -0.397 ($SE$ = 0.403) and the kurtosis statistic

of -0.957 (*SE* = 0.788) suggested that normality was a reasonable assumption. A visual inspection of the Q-Q plot, histogram and box plot for these data supported normality.

d) **Independence:** The Durbin-Watson statistic was computed at 0.937, which was considered acceptable.

e) **Homogeneity of variance:** The spread of regression standardised residuals appeared constant over the range of values of the standardised predicted values. No outliers were evident outside the -3 to 3 value range; this provides evidence of the homogeneity of variance.

f) **Multicollinearity:** A review of the Pearson coefficient correlation matrix of Table 7.3 showed that the calculated -0.415 value was between -0.9 and +0.9. The calculated collinearity statistics indicated that the values of tolerance were above the 0.1 limit and the values of variance inflation factor were less than the 10 value limit. It was reasonable to infer that there was no violation of the multicollinearity assumption.

**Table 7.3 Model 2 Pearson coefficient matrix.**

| Variable | N | Mean | SD | 1. | 2. |
|---|---|---|---|---|---|
| 1. Overall structural condition | 31 | 4.45 | 0.506 | 1.000 | |
| 2. AADT | 31 | 1.71 | 0.783 | -0.415 | 1.000 |

g) **Significant outliers, high leverage and highly influential points:**

a. the maximum Mahalanobis distance was calculated as 8.684 which is above the 5.99 limit established from reference to the Chi-square distribution table. For the purposes of the aims of this research, this violation was nevertheless accepted and outliers were not further considered.

b. the maximum Cook's distance and Central Leverage Value were below the respective 1 and 0.5 limits.

Model 2 is taken as satisfying the assumptions for multiple regression analysis. The results from both models 1 and 2 are presented in Table 7.4.

The prediction model, model 2, contained two of the ten predictors and was reached in two steps, with six outliers removed. The model 2 analysis has produced a significant regression equation ($R^2 = 0.905$, $F(2,28) = 133.938$, $p < 0.001$).

The adjusted $R^2$ value indicated that approximately 90% of the variation in the priority number may be predicted from the derived regression equation:

$$\mathbf{PI = 127.351 - 21.910\ (OSC) - 5.592\ (AADT)} \qquad \mathbf{(17)}$$

where PI is the priority index, OSC is overall structural condition and AADT is annual average daily traffic.

**Table 7.4 Model 1 and 2 regression analysis results.**

| Variable | Model 1 | | Model 2 | |
|---|---|---|---|---|
| | Unstandardised Coefficient | Standardised Coefficient | Unstandardised Coefficient | Standardised Coefficient |
| Intercept | 115.310* | - | 127.351* | |
| Overall structural condition | -19.864* | -0.863 | -21.910* | -1.046 |
| AADT | -4.067* | | -5.592* | -0.413 |
| *N* | 34 | | 31 | |
| F-statistic | 95.480 | | 133.938 | |
| $R^2$ | 0.860 | | 0.905 | |
| Adjusted $R^2$ | 0.851 | | 0.899 | |

$^*p < 0.001$

The statistical analysis has shown that eight of the ten explanatory variables tested (road classification, alternative route, hydraulic vulnerability, structural non-scour condition, rehabilitation cost, design of elevation, material of primary members and number of spans) did not contribute to the multiple regression model. This may be explained by the fact that the sample structures were at or close to failure and were in immediate need of rehabilitation, with the emphasis on immediately addressing those on roadways with the larger traffic volumes. It can therefore be reasonably inferred that the sample of these critical bridges is biased and skewed in favour of structures at or close to failure.

### 7.2.3 Prioritisation index for rehabilitation of non-critical condition bridges.

To cater for the evident bias of critical condition rated bridges, regression analysis was carried out on a sample of non-critical condition 2 ('some damage') and condition 3 ('significant damage') bridges. A randomised sample ($n$ =115) was generated using the SPSS software and the sample was then sorted in Microsoft Excel based on the precedence ranking of the influencing factors from the expert survey identified in Table 7.2.

A multiple regression analysis, using the stepwise method, was conducted on the data sample to establish the best combination of independent variables that predict the dependent or predicted variable, the priority number. The sample was screened for violation of assumptions prior to the analysis and two models were investigated:

- Model 1, which was an exploratory model to identify the independent variables that best predicted the dependent variable and where outliers were labelled and identified, and
- Model 2, where identified outliers were removed from the analysis.

**Model 1.**

a) **Sample size:** The sample size ($n$ = 115) was greater than the necessary 105 required for 15 cases of data for each of the seven explanatory variables (overall structural condition, hydraulic vulnerability, structural non-scour condition, AADT, availability of alternative route, road classification and bridge material type) identified as best predicting the dependent variable.

**b) Linearity:** A review of the scatterplots of the dependent variable (priority number) and the seven independent variables indicated that linearity was a reasonable assumption.

**c) Normality:** The assumption of normality was tested by examination of the standardised residuals. A review of the Kolmogorov-Smirnov test statistic ($K$-$S$ = 0.081, $df$ = 115, $p$ = 0.058), the skewness statistic of -0.315 ($SE$ = 0.226) and the kurtosis statistic of -0.747 ($SE$ = 0.447) suggested that normality was a reasonable assumption. A visual inspection of the Q-Q plot, histogram and box plot for these data supported normality.

**d) Independence:** The Durbin-Watson statistic was computed at 0.547, which was considered acceptable.

**e) Homogeneity of variance:** The spread of regression standardised residuals appeared constant over the range of values of the standardised predicted values. No outliers were evident outside the -3 to 3 value range and this provided evidence of the homogeneity of variance.

**f) Multicollinearity:** A review of the Pearson correlation matrix indicated that all calculated values were between -0.9 and +0.9. The calculated collinearity statistics indicated that the values of tolerance were above the 0.1 limit and the values of variance inflation factor were less than the 10 value limit. It was reasonable to infer that there was no violation of the multicollinearity assumption.

**g) Significant outliers, high leverage and highly influential points:**

- the maximum Mahalanobis distance was calculated as 25.553. By reference to the Chi-square distribution table, with seven degrees of freedom and 95% confidence, the maximum value should be 14.07. There were seven values above this limit and these were therefore labelled as outliers.
- the maximum Cook's distance and Central Leverage Value were below the respective 1 and 0.5 limits.

**Model 2.**

a) **Sample size:** The sample size (*n* = 108) is greater than the necessary 90 required for 15 cases of data for each of the six explanatory variables (overall structural condition, hydraulic vulnerability, structural non scour condition, AADT, availability of alternative route and road classification) identified as best predicting the dependent variable.

b) **Linearity:** A review of the scatterplots of the dependent variable (priority number) and the six independent variables indicated that linearity was a reasonable assumption.

c) **Normality:** The assumption of normality was tested by examination of the standardised residuals. A review of the Kolmogorov-Smirnov test statistic (*K-S* = 0.061, *df* = 108, *p* = 0.2), the skewness statistic of -0.358 (*SE* = 0.233) and the kurtosis statistic of -0.246 (*SE* = 0.461) suggested that normality was a reasonable assumption. A visual inspection of the Q-Q plot, histogram and box plot for these data supported normality.

d) **Independence:** The Durbin-Watson statistic was computed at 0.499, which was considered acceptable.

e) **Homogeneity of variance:** The spread of regression standardised residuals appeared constant over the range of values of the standardised predicted values. No outliers were evident outside the -3 to 3 value range and this provides evidence of the homogeneity of variance.

f) **Multicollinearity:** A review of the Pearson correlation matrix of Table 7.5 showed that all calculated values, which ranged from -0.510 to 0.040, were between -0.9 and +0.9. The calculated collinearity statistics indicated that the values of tolerance were above the 0.1 limit and the values of variance inflation factor were less than the 10 value limit. It was reasonable to infer that there was no violation of the multicollinearity assumption.

**Table 7.5 Model 2 Pearson correlation coefficient matrix.**

| Variable | N | Mean | SD | 1. | 2. | 3. | 4. | 5. | 6. |
|---|---|---|---|---|---|---|---|---|---|
| 1. Overall structural condition | 108 | 2.30 | 0.46 | 1.000 | | | | | |
| 2. Hydraulic vulnerability | 108 | 1.88 | 0.75 | 0.515 | 1.000 | | | | |
| 3. Structural non-scour | 108 | 2.00 | 0.66 | 0.590 | 0.019 | 1.000 | | | |
| 4. AADT | 108 | 1.46 | 0.66 | -0.025 | 0.114 | 0.086 | 1.000 | | |
| 5. Alternative route | 108 | 1.50 | 0.66 | 0.092 | 0.028 | 0.151 | 0.298 | 1.000 | |
| 6. Road class | 108 | 2.32 | 1.06 | -0.103 | -0.270 | 0.040 | -0.510 | -0.367 | 1.000 |

**g) Significant outliers, high leverage and highly influential points:**

- the maximum Mahalanobis distance was calculated as 13.69, which is below the 14.07 limit established from reference to the Chi-square distribution table,
- the maximum Cook's distance and Central Leverage Value were below the respective 1 and 0.5 limits.

Model 2 satisfies the assumptions for multiple regression analysis. The results from both Models 1 and 2 are presented in Table 7.6. The prediction model, Model 2, contained six of the ten predictors and was reached in six steps, with seven outliers removed. The Model 2 analysis has produced a significant regression equation ($R^2 = 0.950$, $F(6,107) = 319.48$, $p < 0.001$). The adjusted $R^2$ value indicates that approximately 95% of the variation in the priority number may be predicted from the derived regression equation:

$$\mathbf{PI = 216.657 - 29.441(HY) - 22.009(OSC) - 13.427(SNS) - 6.922(AR) - 6.751(AADT) - 2.091(RC)} \qquad \mathbf{(18)}$$

where PI is the priority index, HY is hydraulic vulnerability, OSC is overall structural condition, SNS is structural non-scour, AR is alternative route availability, AADT is annual average daily traffic and RC is road classification.

**Table 7.6 Model 1 and 2 regression analysis results.**

| Variable | Model 1 | | Model 2 | |
|---|---|---|---|---|
| | Unstandardised Coefficient | Standardised Coefficient | Unstandardised Coefficient | Standardised Coefficient |
| Intercept | 219.902* | - | 216.657* | - |
| Overall structural condition | -23.025* | -0.322 | -22.099* | -0.301 |
| Hydraulic vulnerability | -28.464* | -0.627 | -29.441* | -0.655 |
| Structural non-scour | -13.081* | -0.262 | -13.427* | -0.263 |
| AADT | -5.825* | -0.128 | -6.751* | -0.133 |
| Alternative route | -5.526* | -0.132 | -6.922* | -0.137 |
| Road class | -1.769** | -0.057 | -2.091** | -0.066 |
| Bridge material type | -2.150** | -0.061 | - | - |
| *N* | 115 | | 108 | |
| F-statistic | 277.22 | | 319.48 | |
| $R^2$ | 0.948 | | 0.950 | |
| Adjusted $R^2$ | 0.944 | | 0.947 | |

$^{*}p < 0.001$, $^{**}p < 0.05$

### 7.2.4 Overall bridge stock prioritisation indices.

This research proposes an enhanced methodology relative to that of Valenzuela et al. (2010) in that, while both undertake a survey of expert practitioners to identify the influencing variables, the availability and analysis of a record for critical structure rehabilitations indicates that two separate indices apply in the formation of judgements for the ranking of rehabilitation projects:

- an index for structures in a critical condition based on the values of the overall structural condition and AADT variables, with the overall structural condition parameter being the most influential.
- an index for structures in a non-critical condition based on the values of hydraulic vulnerability, the overall structural condition, the structural non-scour condition, the availability of an alternative route, the AADT and the road classification, with their influence ranked in that order.

The derived indices are applied to all the structures in the dataset by sorting and ranking in Microsoft Excel and thus provide a prioritised list for further analysis.

## 8.0 Performance model for bridge rehabilitation strategies.

The constituent elements of the performance model proposed by this research are described in this section.

**(i). Definition of strategy time horizon.**

An annual deterioration rate of 0.057 in bridge condition rating has been established and equates to a one point reduction in rating every 17.5 years. As funding is granted on an annual basis, this is rounded to a whole year value of 17 years. A strategy time horizon of 85 years is chosen for this study, which is equivalent to the transition time required for a bridge condition rated 0 to deteriorate, without rehabilitation, to a condition rated 5 structure i.e. the strategy time horizon is made up of five separate planning periods of 17 years, with strategy commencement at $T_0$ and five separate planning periods concluding at $T_1$ (17 years), $T_2$ (34 years), etc. This is in line with the 15 to 20 year planning periods for transportation projects reported by Sinha and Labi (2011, p.500).

**(ii). Application of a standard economic appraisal method.**

In Ireland, the Department of Public Expenditure and Reform requires the economic appraisal of capital investments by the State in projects costing in excess of €20 million (DPER, 2011, p.3) and states that the Net Present Value (NPV) method is fundamental to proper appraisal of projects and programmes (DPER, 2015a, p.126).

**(iii). Utilisation of performance indicators.**

A performance indicator is a measurable value that shows the progress in the achievement of project or process goals and indicates whether an initiative has attained its goals in a specific time frame. The strategy performance indicators of ‘effectiveness’ and ‘efficiency’ are proposed for this research.

- **Strategy effectiveness**

  Effectiveness is defined by the British Standards Institution as the “extent to which planned activities are realised and planned results are achieved” (BSI, 2015, p.22). This research uses the UK County Surveyors’ Society Bridge Stock Condition Index (BSCI) concept where the Bridge Condition Indicators (BCIs) of each bridge on a network may be used to calculate a single numerical indicator value, termed the BSCI, for an entire bridge stock (Atkins, 2002, pp.28-30).

- **Strategy efficiency**

  The concept that the efficiency of a strategy may be represented by the cost to move the full asset from its actual condition to an ‘as new’ condition has been reported by Orcesi and Cremona (2011) for bridges on the French national route system and by Horak et al. (2001) for the road network system managed by the New Zealand Transport Agency. A reduction of this cost means that the quality of the asset improves. Conversely, an increase means that the value of the asset is degrading.

**(iv). Evaluation of strategy performance**

A comparison of the calculated effectiveness and efficiency parameters allows an evaluation of the performance or productivity of different strategies (McGee, 2004). This is shown graphically in Figure 8.1 where the ‘slope of productively’ or ‘ideal performance line’, plotted at $45^0$, represents the best balance between ‘effectiveness’ and ‘efficiency’.

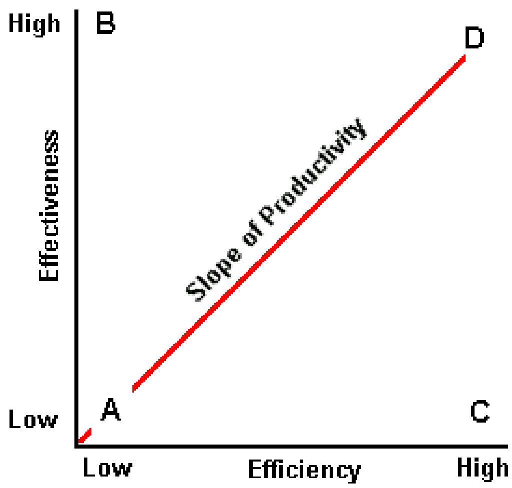
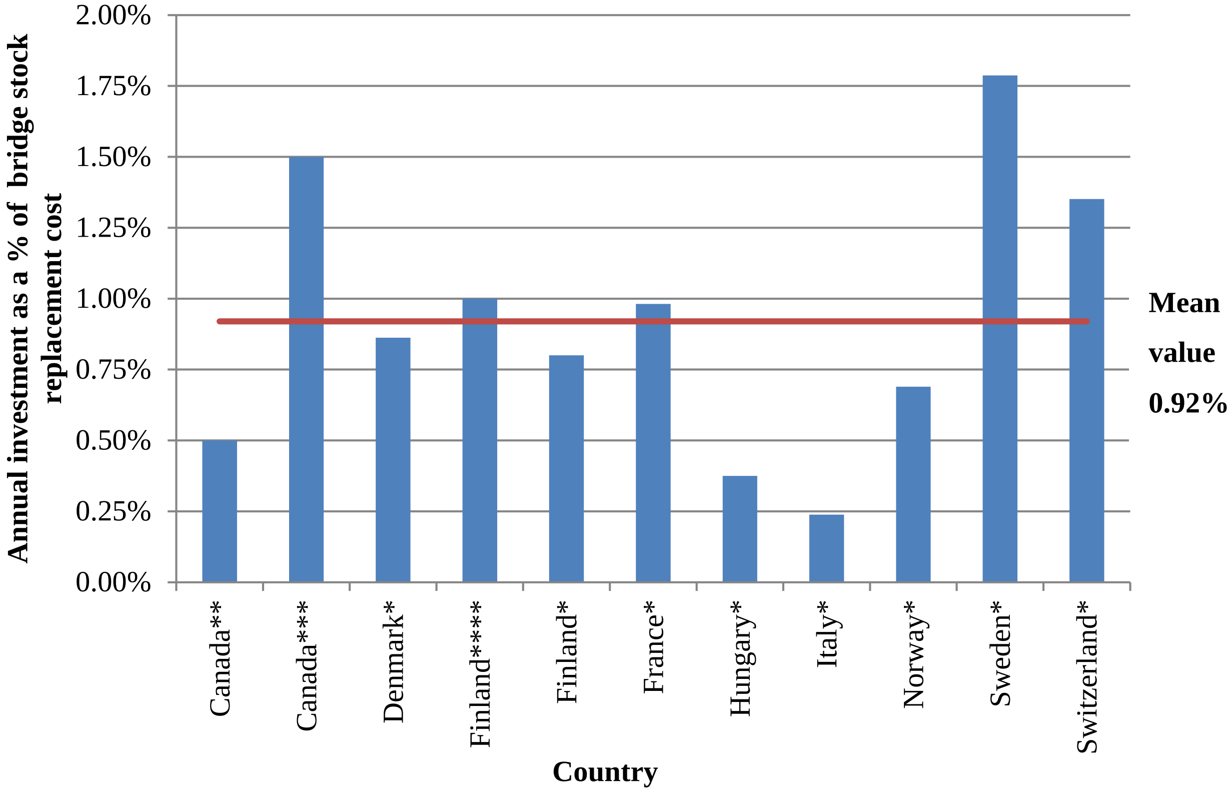



**Figure 8.1. Effectiveness, efficiency and performance (McGee, 2004).**

Strategy A, which has low effectiveness and low efficiency, has low performance. Strategy B, while highly effective, has low performance, because it has low efficiency. Strategy C, while highly efficient, has low effectiveness and therefore has low performance. Strategy D, which is highly effective and highly efficient, has a high performance.

**(v). Benchmark comparison with international practice.**

To inform the formulation of strategies and to allow a benchmark comparison, a review of international practice and research into annual investment values has been undertaken. The reported values, expressed as percentages of a bridge stock replacement cost, are shown in Figure 8.2 and range from 0.24% in Italy to 1.79% in Sweden. To establish a central tendency value for these data, normality testing was undertaken using SPSS. A Shapiro-Wilks test ($p > 0.05$) and a visual inspection of their histogram, normal Q-Q plot and box plot showed that these values are approximately normally distributed with a skewness of 0.438 (SE = 0.661) and a kurtosis of -0.468 (SE = 1.279). These data are thus taken as being normally distributed with a mean value (*M*) of 0.92% and a standard deviation (*SD)* of 0.48.




(*PIARC, 2004; **McCarten, 2006; ***Mirza, 2006; ****Kähkönen and Marshall, 1990)

**Figure 8.2 International annual investments in bridge stock rehabilitation.**

## 9.0 Development and testing of strategies.

This research investigates five strategies:

- a no investment scenario,
- a minimum achievement scenario,
- the existing investment scenario
- scenarios of 1% and 1.5% of bridge stock replacement value investment levels respectively, which are based on the reported range of international practice.

A strategy time horizon of 85 years is assumed. To establish the cost of each strategy, the methodology used has taken into account the fact that each structure deteriorates over time. To illustrate by way of an example, a bridge rated condition 2 with a known rehabilitation cost (i.e. the cost to improve from a condition 2 to condition 0, as recorded in the Eirspan dataset) at the strategy commencement will deteriorate, with no rehabilitation, to a condition 3 after 17 years and to a condition 4 after 34 years. For this study, the rehabilitation cost of this condition 4 structure at year 34 is taken as the cost as recorded in the Eirspan dataset at condition 2 plus a statistically derived additional cost (described in Figure 9.1) to improve from a condition 4 to 3 plus a further statistically derived additional cost to improve from a condition 3 to 2. As an example, a bridge with a condition rating of 2 at the strategy commencement and an arbitrary cost of €20,000 will deteriorate to condition 3 after 17 years (where it will have a cost of €20,000 + €2,337 = €22,377) and then to condition 4 after 34 years (where it will have a cost of €20,000 + €2,337 + 3,735 = €26,072). This value of €26,072 represents the cost of rehabilitating the condition rated 4 structure to condition 0.

Rehabilitation cost information is available from the Eirspan database for 1,278 bridges, with a total bridge stock cost of €24,232,263. The cost estimated value data for each of the condition ratings are tested with SPSS software for normality. Kolmogorov-Smirnov and Shapiro-Wilks tests and visual inspections of their histograms, normal Q-Q plots and box plots showed that for all six condition rating groups, cost data are not normally distributed (p

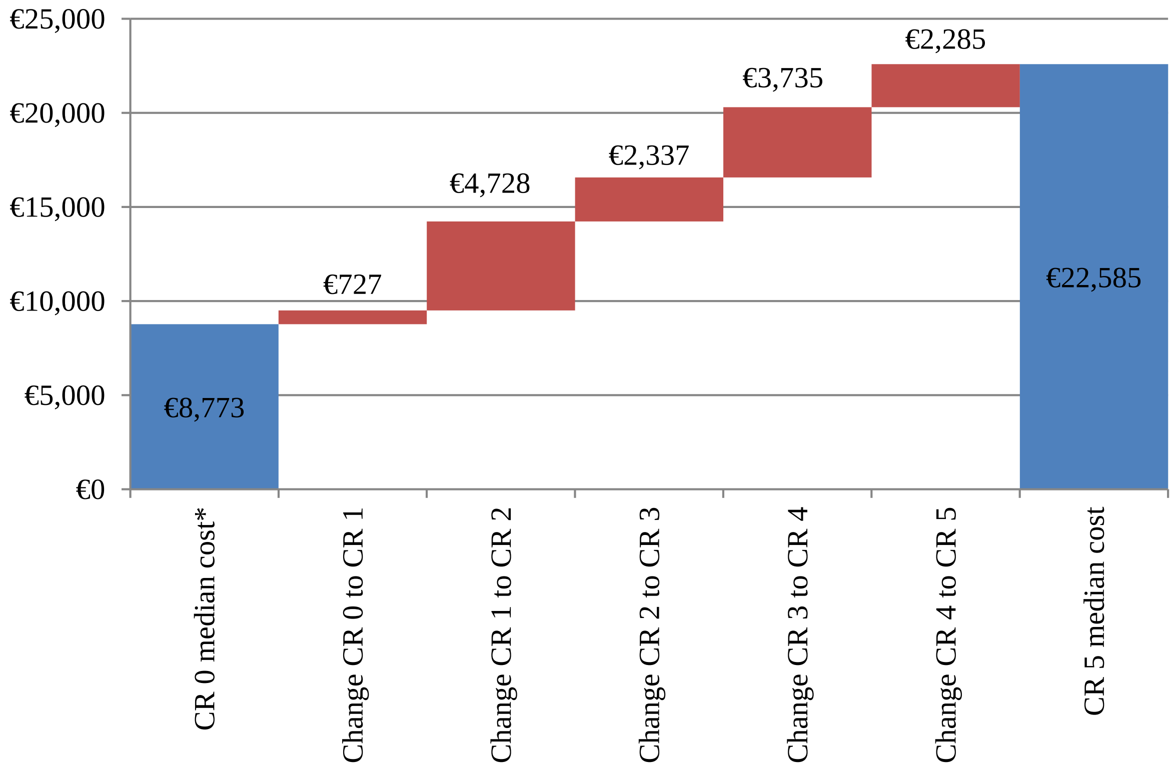
> 0.05). The median values, shown in Table 9.1, are thus taken as the measures of central tendency of these cost data.

**Table 9.1. Increase in cost of rehabilitation projects with condition rating deterioration.**

| Condition rating (No.) | No. of bridges (*N*) | Total rehabilitation cost (€) | Median cost (*Mdn*) (€) | Interquartile range (*IQR*) (€) | Range ($Q_1$, $Q_3$) (€) |
|---|---|---|---|---|---|
| 0* | 27 | 307,353 | 8,773 | 10,865 | (4,920, 15,785) |
| 1 | 164 | 2,404,077 | 9,500 | 13,724 | (4,281, 18,005) |
| 2 | 718 | 12,323,422 | 14,228 | 14,019 | (7,787, 21,806) |
| 3 | 266 | 6,131,431 | 16,565 | 14,970 | (9,122, 24,092) |
| 4 | 74 | 2,137,290 | 20,300 | 26,505 | (9,350, 35,855) |
| 5 | 29 | 928,690 | 22,585 | 19,723 | (15,130, 34,853) |

* Some condition 0 rated structures have a cost value as the Eirspan system records improvement costs for non-critical components that do not influence the assignment of overall ratings e.g. repair to bridge surfacing.

The change or difference in median values is shown in Figure 9.1 and provides an estimate of the increase in rehabilitation cost when a structure deteriorates and transitions from a particular rating to a higher rating.




* Some condition 0 rated structures have a cost value as the Eirspan system records improvement costs for non-critical components that do not influence the assignment of overall ratings e.g. repair to bridge surfacing.

**Figure 9.1. Increases in rehabilitation cost for condition rating transition.**

The individual strategy parameters were established by:

- ranking projects based on the calculated prioritisation indices,
- applying a consistent condition deterioration rate of 0.057 per annum to each structure,
- calculating the time required to achieve full bridge stock rehabilitation based on the annual investment values for each strategy.

The calculations yielded the following results:

- Strategy 1 (€0/annum). All bridges deteriorate to condition 5 at the end of 85 years. The percentage condition ratings of the bridge stock in terms of planning time periods $T_1$, $T_2$, etc, are shown in Figure 9.2. It is evident from Figure 9.2 that the bridge stock deteriorates from its initial range of condition ratings at $T_0$ (CR 0: 2.56%, CR 1: 13.62%, CR 2: 55.08%, CR 3: 20.47%, CR 4: 6.09% and CR 5: 2.18%) and reduces in quality until $T_5$ when all structures are at condition rating 5.

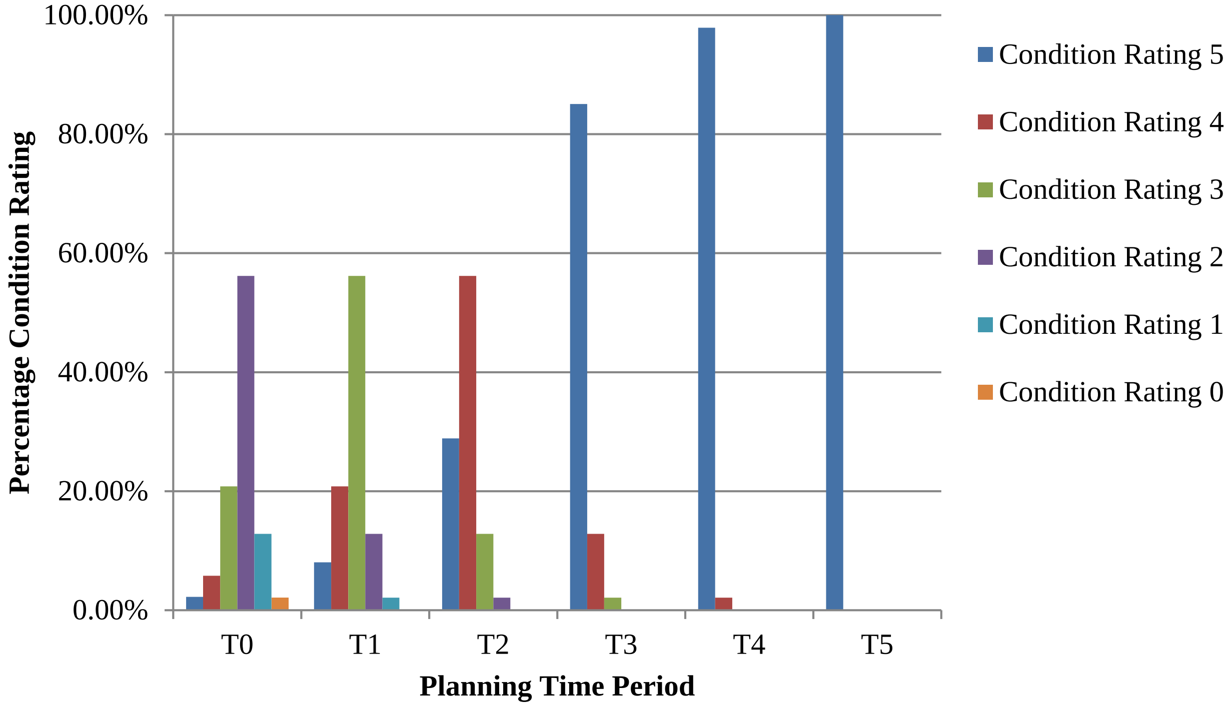



**Figure 9.2. Strategy 1 - percentage condition ratings of the bridge stock by planning time period.**

- Strategy 2 (€545,000/annum): The minimum annual investment required to achieve rehabilitation of all structures to a minimum of condition rating 1 within the strategy time horizon has been calculated as €545,000. Each bridge is rehabilitated twice during the 85 year planning horizon and there is an average of 30 projects per annum. This represents an annual investment of 0.27% of the bridge stock replacement cost, calculated from the estimated bridge stock asset value of €204,190,000 described in Section 5.6. The percentage condition ratings of the bridge stock in terms of planning time periods $T_1$, $T_2$, etc, are shown in Figure 9.3:

- at $T_0$, the initial range of condition ratings are CR 0: 2.56%, CR 1: 13.62%, CR 2: 55.08%, CR 3: 20.47%, CR 4: 6.09% and CR 5: 2.18%,
- at $T_1$, all CR 5 structures are rehabilitated, the number of CR 3 bridges has increased as CR 2 bridges at $T_0$ deteriorate and the number of CR 0 bridges increases,
- at $T_2$, the number CR 0 and CR 1 bridges increases as the strategy progresses,
- at $T_3$, there are no CR 4 or CR 5 structures in the bridge stock,
- at $T_4$, bridge stock consists on CR 0, CR 1 and CR 2 structures only,
- at $T_5$, all bridges are either CR 0 (41%) or CR 1 (59%).

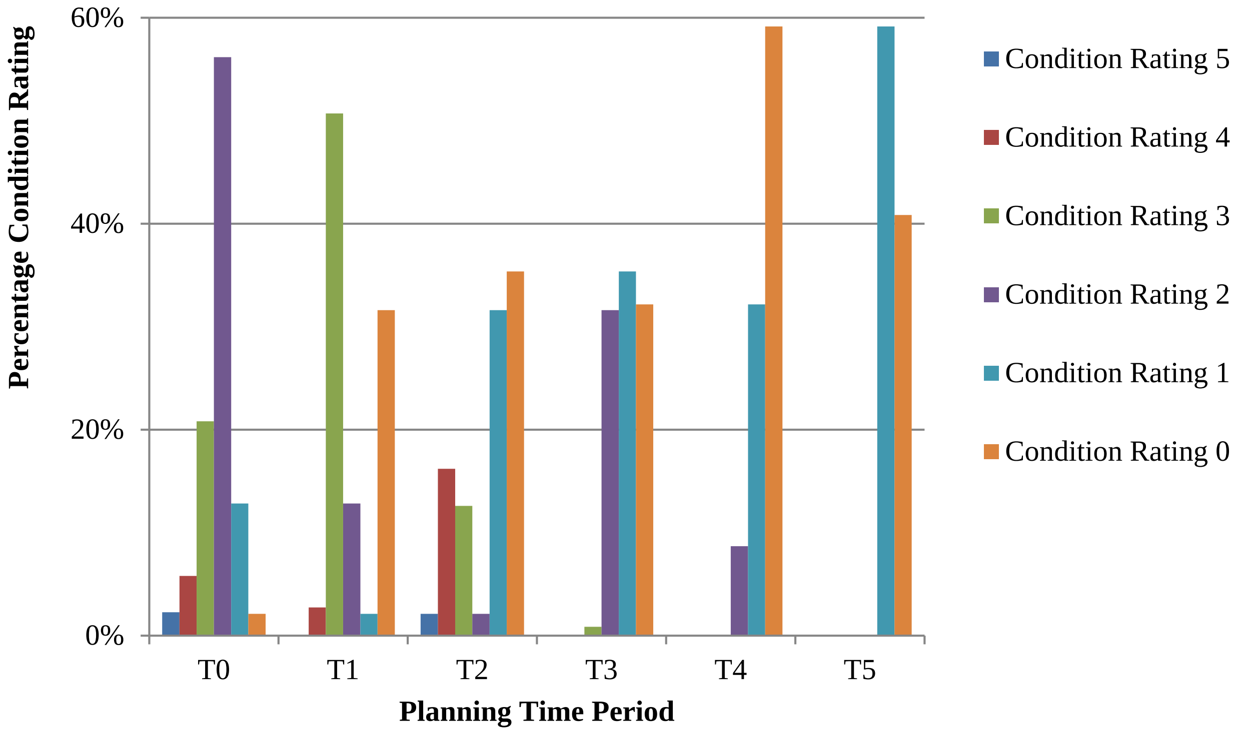



**Figure 9.3. Strategy 2 - percentage condition ratings of the bridge stock by planning time period.**

- Strategy 3 (€870,000/annum): This is the existing strategy and represents an annual investment of 0.43% of the bridge stock replacement cost, as calculated in Section 5.8. All structures are rehabilitated to condition rating 0 at the end of 27 years and there is an average of 47 projects per annum. After year 27, the bridges degrade over the 17 year deterioration cycle to condition rating 1 at the end of year 44. An investment of 1,278 x €9,500 = €12,141,000 (taken from the calculated data of Figure 9.1) is therefore required from year 45 to year 61 to return the bridge stock to condition rating 0. This equates to €714,176 per annum and this investment is again required for years 79 to 96 (ceasing in this analysis at year 85), with an average of 76 projects per annum for these periods. For this strategy, each bridge is rehabilitated at least twice during the 85 year planning horizon. The percentage condition ratings of the bridge stock are shown in Figure 9.4 in terms of planning time periods:
    - at $T_0$, the initial range of condition ratings is CR 0: 2.56%, CR 1: 13.62%, CR 2: 55.08%, CR 3: 20.47%, CR 4: 6.09% and CR 5: 2.18%,
    - at $T_1$, all CR 5 structures are rehabilitated, the number of CR 3 bridges has increased as CR 2 bridges at $T_0$ deteriorate and the number of CR 0 bridges increases to 54%,
    - at $T_2$, all bridges are either CR 0 (59%) or CR 1 (41%),
    - at $T_3$, all bridges are either CR 0 (41%) or CR 1 (59%).
    - at $T_4$, all bridges are either CR 0 (59%) or CR 1 (41%),
    - at $T_5$, all bridges are either CR 0 (41%) or CR 1 (59%).

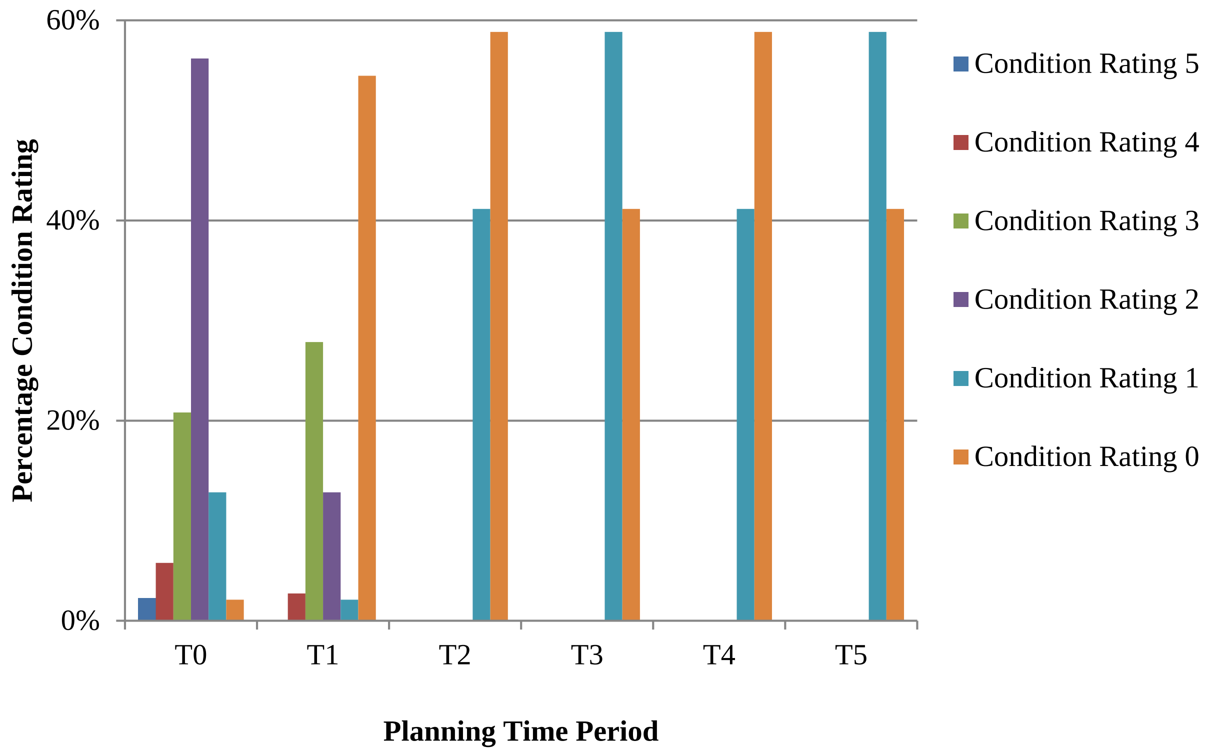



**Figure 9.4. Strategy 3 - percentage condition ratings of the bridge stock by planning time period.**

- Strategy 4 (€2,000,000/annum): This represents an annual investment of 1% of the bridge stock replacement cost and all structures are rehabilitated to condition rating 0 at the end of 12 years. There is an average of 106 projects per annum. After year 12, the bridges degrade over the 17 year deterioration cycle to condition rating 1 at the end of year 29. An investment of 1,278 x €9,500 = €12,141,000 (taken from the calculated data of Figure 9.1) is therefore required from year 30 to year 46 to return the bridge stock to condition rating 0. This equates to €714,176 per annum and this investment is again required for years 64 to 80, with an average of 76 projects per annum for these periods. From year 81, the bridge stock again deteriorates. For this strategy, each bridge is rehabilitated three times during the 85 year planning horizon. The percentage condition ratings of the bridge stock are shown in Figure 9.5 in terms of planning time periods:

- at $T_0$, the initial range of condition ratings is CR 0: 2.56%, CR 1: 13.62%, CR 2: 55.08%, CR 3: 20.47%, CR 4: 6.09% and CR 5: 2.18%,
- at $T_1$, all bridges are either CR 0 (71%) or CR 1 (29%),
- at $T_2$, all bridges are either CR 0 (29%) or CR 1 (71%),
- at $T_3$, all bridges are either CR 0 (71%) or CR 1 (29%),
- at $T_4$, all bridges are either CR 0 (29%) or CR 1 (71%),
- at $T_5$, all bridges are either CR 0 (71%) or CR 1 (29%).

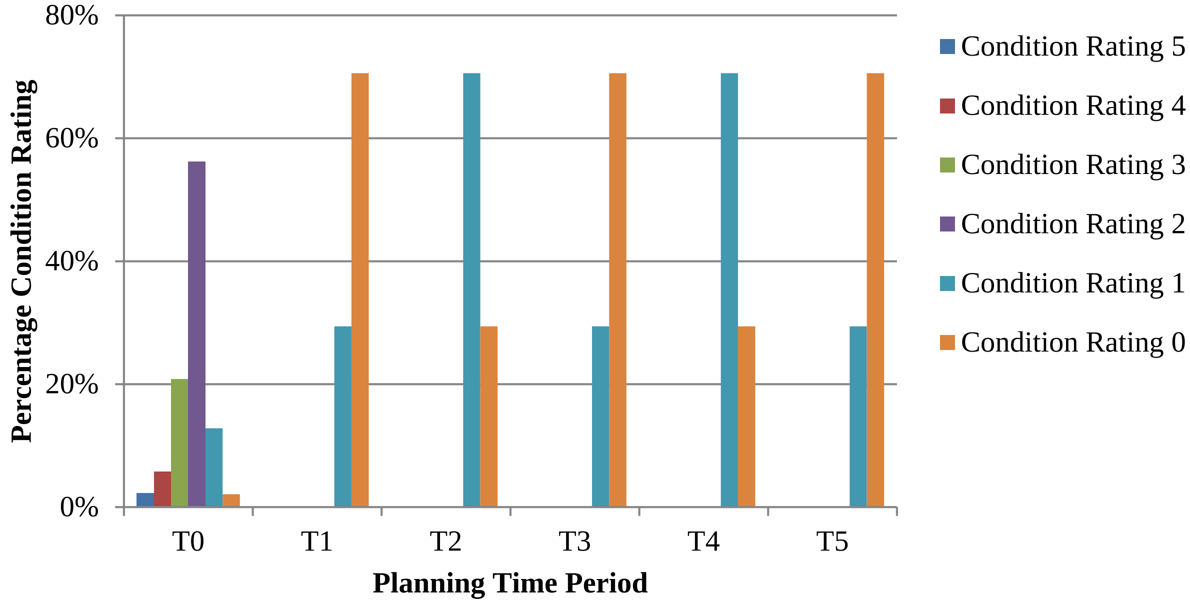



**Figure 9.5. Strategy 4 - percentage condition ratings of the bridge stock by planning time period.**

- Strategy 5 (€3,000,000/annum): This equates to an annual investment of 1.5% of the bridge stock replacement cost and all structures are rehabilitated at the end of 8 years. There is an average of 160 projects per annum. After year 8, the bridges degrade over the 17 year deterioration cycle to condition rating 1 at the end of year 25. An investment of 1,278 x €9,500 = €12,141,000 (taken from the calculated data of Figure 9.1) is therefore required from year 26 to year 42 to return the bridge stock to condition rating 0. This equates to €714,176 per annum and this investment is again required for years 60 to 76, with an average of 76 projects per annum for these periods. From year 77, the bridge stock again deteriorates. For this strategy, each bridge is rehabilitated three times during the 85 year planning horizon. The percentage condition ratings of the bridge stock are shown in Figure 9.6 in terms of planning time periods:

- at $T_0$, the initial range of condition ratings is CR 0: 2.56%, CR 1: 13.62%, CR 2: 55.08%, CR 3: 20.47%, CR 4: 6.09% and CR 5: 2.18%,
- at $T_1$, all bridges are either CR 0 (47%) or CR 1 (53%),
- at $T_2$, all bridges are either CR 0 (49%) or CR 1 (51%),
- at $T_3$, all bridges are either CR 0 (47%) or CR 1 (53%),
- at $T_4$, all bridges are either CR 0 (49%) or CR 1 (51%),
- at $T_5$, all bridges are either CR 0 (47%) or CR 1 (53%).

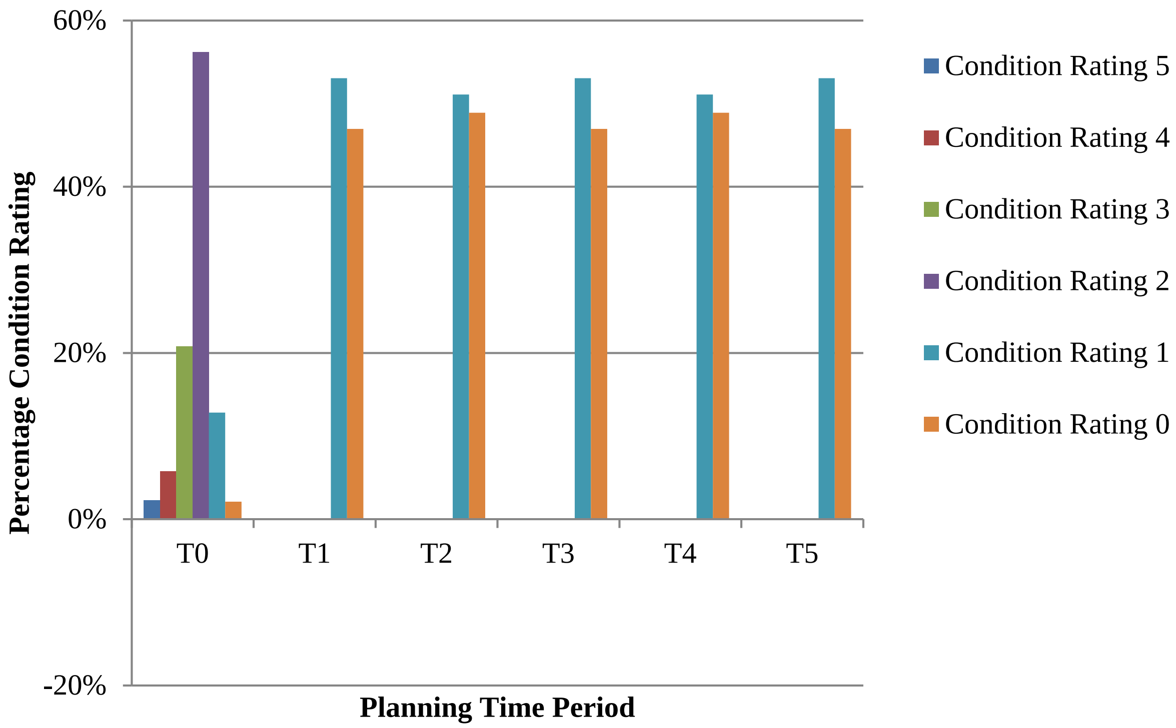



**Figure 9.6. Strategy 5 - percentage condition ratings of the bridge stock by planning time period.**

A comparison of the five strategies shows that they can be broadly classified into three groups:

1. Strategy 1, where there is no rehabilitation and all structures ultimately reach CR 5.
2. Strategy 2, where all bridges, with a consistent annual investment of €545,000 over the strategy time horizon of 85 years, are rehabilitated to a minimum of CR 1.
3. Strategy 3 (€870,000/annum for 27 years), Strategy 4 (€2,000,000/annum for 12 years) and Strategy 5 (€3,000,000/annum for 8 years), where all bridges are rehabilitated to a minimum of CR 1 and due to structural deterioration over time, require an intermittent investment of €712,176 per annum.

The standard economic appraisal technique of Net Present Value (NPV) is applied to the developed strategies. The NPV method is a budgeting procedure that informs the investment decision on capital projects and may be expressed as a formula to determine the present value of an investment by the discounted sum of all cash flows received from the project (Cassimatis, 1998, p.43):

$$\mathrm{NPV} = \sum_{t=1}^{T} \frac{C_t}{(1+r)^t} - C_o \qquad \textbf{(19)}$$

where:

$C_t$ = net cash inflow during the period t,

$C_o$ = total initial investment costs,

r = discount interest rate, and

t = number of time periods.

Typical discount rates used for evaluating public investments range from 4% to12% (Litman, 2006, p.9). In Ireland, the discount rate for economic appraisal is set at 5% (DPER, 2015b, p.1). If the present value of the cash flows is equal to or greater than the cost of the investment, the project is profitable and should be accepted. In comparing a range of project options, the option which yields the highest NPV value in terms of income is the preferred option. The strategies identified in this research differ in terms of annual investment patterns:

- Strategy 2 has equal payment amounts over the 85 year planning horizon.
- Strategies 3, 4 and 5 have unequal payment patterns, with a high level of investment at the start of each strategy and an intermittent level of investment as the strategies develop.

Besley and Brigham (2008, pp.147-153) provide methodologies for the calculation of both equal and unequal investment patterns, given the discount rate:

- for an equal series of payments:

$$PV = A \left[ \frac{1 - \frac{1}{(1+r)^n}}{r} \right] \quad \textbf{(20)}$$

- for an unequal series of payments:

$$PV = \frac{A_1}{(1+r)^1} + \frac{A_2}{(1+r)^2} + \ \ldots\ldots + \frac{A_n}{(1+r)^n} \quad \textbf{(21)}$$

where:
PV = present value of total investment
A = investment amount for an equal series of payments
An = investment amount for an unequal series of payments
i = discount interest rate, and
n = number of time periods

The methodologies are applied to the indentified strategies and the results presented in Table 9.2.

**Table 9.2. NPV assessment of intervention strategies.**

| Strategy | Description | NPV (€) |
|---|---|---|
| 2 | Equal annual investments of €545,000 from $T_1$ (year 1) to $T_5$ (year 85) | -10,736,296 |
| 3 | Unequal and intermittent series of annual investments of:<br>• €870,000 from $T_1$ (year 1) to year 27<br>• €714,176 from year 45 to year 61<br>• €714,176 from year 79 to year 85 | -13,783,048 |
| 4 | Unequal and intermittent series of annual investments of:<br>• €2,000,000 from $T_1$ (year 1) to year 12<br>• €714,176 from year 30 to year 46<br>• €714,176 from year 64 to year 80 | -20,054,984 |
| 5 | Unequal and intermittent series of annual investments of:<br>• €3,000,000 from $T_1$ (year 1) to year 8<br>• €714,176 from year 26 to year 42<br>• €714,176 from year 60 to year 76 | -22,219,921 |

The calculated annual NPV values are included in Appendix D. As the investments are costs, they are presented as negative values. The lowest cost option, which is Strategy 2, is the preferred strategy using the NPV assessment method.

There are limitations with this assessment in terms of its application to a multiple project strategy such as a bridge stock rehabilitation process, where the stock is continuously deteriorating. The NPV method does not provide a clear indication of the performance of a strategy in terms of ongoing achievement of results and does not quantify improvement in the bridge stock.

To address these shortcomings, this research proposes the use of performance indicators, which are described in Section 8.0.

### (i). Strategy effectiveness.

The UK County Surveyors' Society parameter of BCI and BSCI are used, with the Eirspan condition ratings taken as the BCIs and the deck area values taken from the inventory records. The BSCI is calculated by taking the individual BCI values, weighted by the square metre deck area of each bridge, using the formula:

$$BSCI = \frac{\sum_{i=1}^{n} (BCI \ x \ Deck \ area)}{\sum_{i=1}^{n} (Deck \ area)} \qquad (22)$$

The BSCIs at the start of the strategy and at each 17 year planning period have been calculated and are shown in Table 9.3. The BSCIs have a starting global value of 2.16 on a scale from 0 to 5. The calculated annual BSCI values are included in Appendix D.

**Table 9.3. Strategy BSCI values.**

| Time period | Strategy 1 | Strategy 2 | Strategy 3 | Strategy 4 | Strategy 5 |
|---|---|---|---|---|---|
| $T_0$ | 2.16 | 2.16 | 2.16 | 2.16 | 2.16 |
| $T_1$ | 3.15 | 1.84 | 1.23 | 0.29 | 0.53 |
| $T_2$ | 4.08 | 1.59 | 0.41 | 0.71 | 0.47 |
| $T_3$ | 4.79 | 1.00 | 0.59 | 0.29 | 0.53 |
| $T_4$ | 4.97 | 0.50 | 0.41 | 0.71 | 0.47 |
| $T_5$ | 5.00 | 0.58 | 0.59 | 0.29 | 0.53 |

This study uses as the measure of effectiveness the ratio of the BSCI at the start of the strategy ($T_0$) to the BSCI at the start of each planning period ($T_1$, $T_2$, etc):

$$\textbf{Strategy effectiveness} = \frac{\textbf{BSCI at start of strategy}}{\textbf{BSCI at start of each planning period}} \qquad (23)$$

To illustrate by way of example, at $T_2$ the strategy effectiveness value for Strategy 3 is 2.16 ÷ 0.41 = 5.27. The calculated values for all strategies are shown graphically in Figure 9.7:

- Strategy 1, with no investment, worsens in condition to an effectiveness indicator value of 0.43 at $T_5$,
- Strategy 2 improves from $T_0$ to $T_4$, but decreases from $T_4$ to $T_5$. At $T_4$, the composition of the bridge stock is 59% CR 0, 32% CR 1 and 9% CR 2. At $T_5$, the composition of the bridge stock is 41% CR 0 and 59% CR 1. The transition from $T_4$ to $T_5$ has achieved the strategy objective of returning all structures to either CR 0 or CR 1 but, as the number of CR 0 has reduced from 59% to 41% with an increase in CR 1 from 32% to 59% due to deterioration over time, the effectiveness parameter for $T_5$ has decreased.
- Strategy 3, which has achieved completion (all bridges either CR 0 or CR 1) at the end of 27 years, improves from $T_0$ to $T_2$, but the effectiveness parameter alternates in value from $T_2$ to $T_5$ between 5.27 and 3.66. At $T_2$, the composition of the bridge stock is 59% CR 0 and 41% CR 1. At $T_3$, the composition of the bridge stock is 41% CR 0 and 59% CR 1. The reduction in effectiveness is attributable to deterioration over time, while the improvement is due to the intermittent investment of €712,196 per annum previously described.
- Strategy 4, which has achieved completion at the end of 12 years, improves from $T_0$ to $T_1$, but the effectiveness parameter alternates in value from $T_1$ to $T_5$ between 7.45 and 3.04. This range in value variation is wider than that of Strategy 3 (and of Strategy 5) and may be accounted for by the relative closeness of the start of Year 13 (when the BSCI for this strategy was 0, as is evident from the data in Appendix D) to the start of year 18 ($T_1$).

- Strategy 5, which has achieved completion at the end of 8 years, improves from $T_0$ to $T_1$, but the effectiveness parameter alternates in value from $T_1$ to $T_5$ between 4.08 and 4.6. This range in value variation is not as wide as either Strategy 3 or Strategy 4. At $T_1$, the composition of the bridge stock is 47% CR 0 and 53% CR 1. At $T_2$, the composition of the bridge stock is 49% CR 0 and 52% CR 1. The values in turn alternate for $T_3$ to $T_5$. As previously, the reduction in effectiveness is attributable to deterioration over time, while the improvement is due to the intermittent investment of €712,196 per annum previously described.

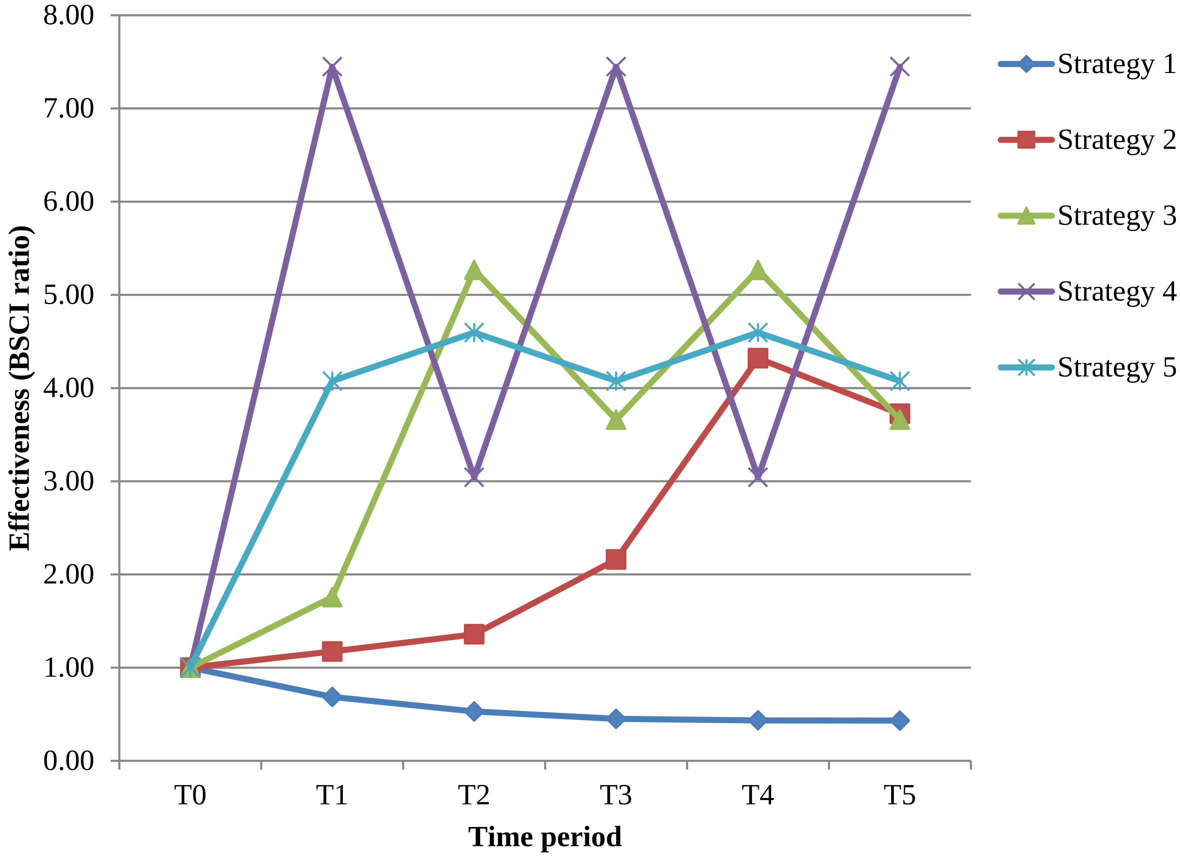



**Figure 9.7. Strategy effectiveness.**

**(ii). Strategy efficiency.**

This research proposes the concept that the efficiency of a strategy may be represented by the cost to move the full asset from its actual condition to an 'as new' condition. This methodology has been used on the French national route system (Orcesi and Cremona, 2011) and New Zealand Transport Agency road network system (Horak et al., 2001). A reduction of this cost means that the quality of the asset improves. Conversely, an increase means that the value of the asset is degrading. The technique has been applied to the subject data, with the cost estimates taken from the Eirspan database. The calculated annual rehabilitation cost values are included in Appendix D. The total rehabilitation costs at the start of the strategy and at the start of each 17 year planning period have been calculated and are shown in Table 9.4.

**Table 9.4. Strategy total rehabilitation costs.**

| Time period | Strategy 1 (€) | Strategy 2 (€) | Strategy 3 (€) | Strategy 4 (€) | Strategy 5 (€) |
|---|---|---|---|---|---|
| $T_0$ | 24,232,263 | 24,232,263 | 24,232,263 | 24,232,263 | 24,232,263 |
| $T_1$ | 27,868,568 | 17,406,983 | 11,115,027 | 3,570,882 | 6,427,588 |
| $T_2$ | 31,368,411 | 13,360,427 | 4,999,235 | 8,570,118 | 5,713,412 |
| $T_3$ | 32,144,617 | 10,319,550 | 7,141,765 | 3,570,882 | 6,427,588 |
| $T_4$ | 32,245,462 | 5,483,808 | 4,999,235 | 8,570,118 | 5,713,412 |
| $T_5$ | 32,307,157 | 7,182,000 | 7,141,765 | 3,570,882 | 6,427,588 |

This study uses as the measure of efficiency the ratio of the total rehabilitation cost value at the start of the strategy ($T_0$) to the total rehabilitation cost value at the start of each planning period ($T_1$, $T_2$, etc) i.e.:

$$\textbf{Strategy efficiency} = \frac{\textbf{Total rehabilitation cost at start of strategy}}{\textbf{Total rehabilitation cost at start of planning period}} \qquad (24)$$

To illustrate by way of example, at $T_2$ the strategy efficiency value for Strategy 3 is 24,232,263 ÷ 4,999,235 = 4.85. The calculated values for all strategies are shown graphically in Figure 9.8:

- Strategy 1, with no investment, worsens in condition to an efficiency indicator value of 0.75 at $T_5$,
- Strategy 2 improves from $T_0$ to $T_4$, but decreases from $T_4$ to $T_5$. At $T_4$, the composition of the bridge stock is 59% CR 0, 32% CR 1 and 9% CR 2. At $T_5$, the composition of the bridge stock is 41% CR 0 and 59% CR 1. The transition from $T_4$ to $T_5$ has achieved the strategy objective of returning all structures to either CR 0 or CR 1 but, as the number of CR 0 has reduced from 59% to 41% with an increase in CR 1 from 32% to 59% due to deterioration over time, the efficiency parameter for $T_5$ has decreased.
- Strategy 3, which has achieved completion (all bridges either CR 0 or CR 1) at the end of 27 years, improves from $T_0$ to $T_2$, but the efficiency parameter alternates in value from $T_2$ to $T_5$ between 4.85 and 3.39. At $T_2$, the composition of the bridge stock is 59% CR 0 and 41% CR 1. At $T_3$, the composition of the bridge stock is 41% CR 0 and 59% CR 1. The reduction in efficiency is attributable to deterioration over time, while the improvement is due to the intermittent investment of €712,196 per annum previously described.
- Strategy 4, which has achieved completion at the end of 12 years, improves from $T_0$ to $T_1$, but the efficiency parameter alternates in value from $T_1$ to $T_5$ between 6.79 and 2.83. This range in value variation is wider than that of Strategy 3 (and of Strategy 5) and may be accounted for by the relative closeness of the start of Year 13 (when the rehabilitation cost for this strategy was 0, as is evident from the data in Appendix D) to the start of year 18 ($T_1$).
- Strategy 5, which has achieved completion at the end of 8 years, improves from $T_0$ to $T_1$, but the efficiency parameter alternates in value from $T_1$ to $T_5$ between 3.77 and 4.24. This range in value variation is not as wide as either Strategy 3 or

Strategy 4. At $T_1$, the composition of the bridge stock is 47% CR 0 and 53% CR 1. At $T_2$, the composition of the bridge stock is 49% CR 0 and 52% CR 1. The values in turn alternate for $T_3$ to $T_5$. As previously, the reduction in efficiency is attributable to deterioration over time, while the improvement is due to the intermittent investment of €712,196 per annum previously described.

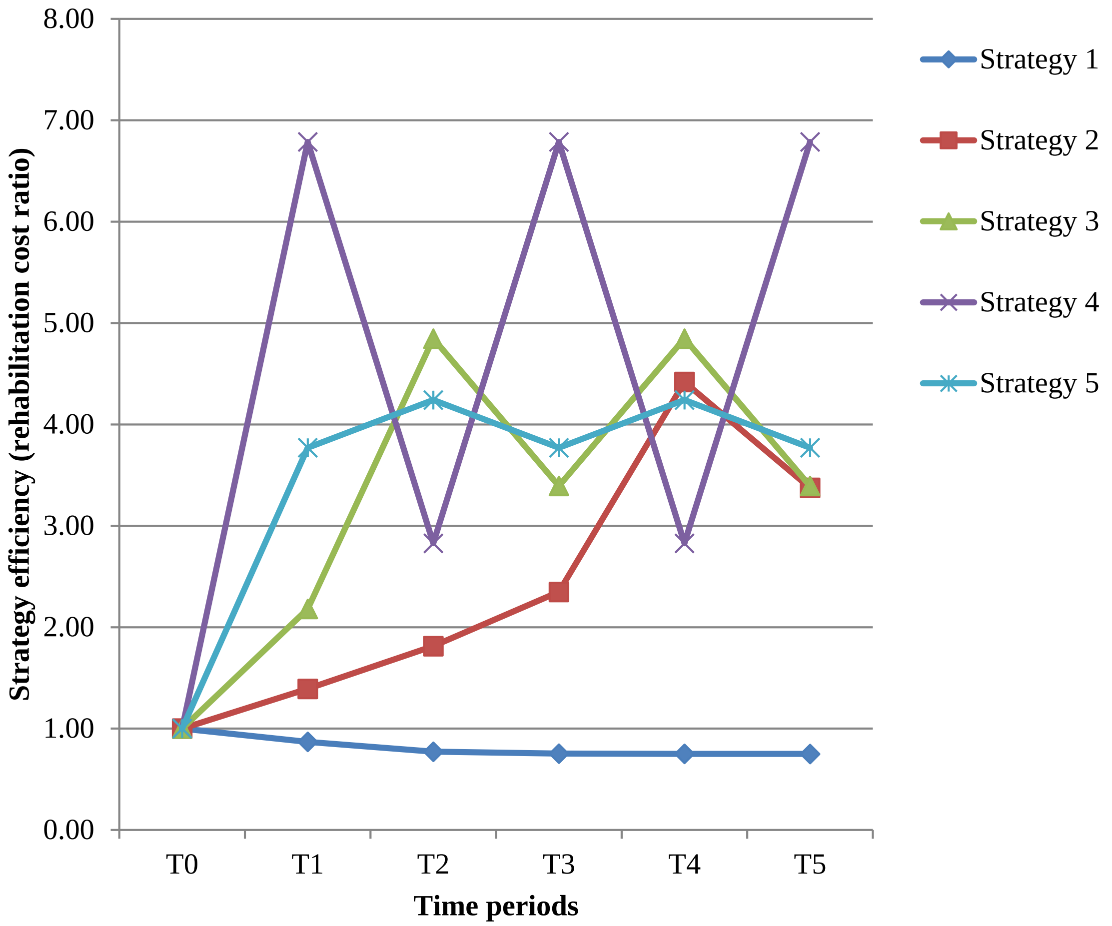



**Figure 9.8. Strategy efficiency.**

### (iii). Strategy performance.

Strategy performance is evaluated in terms of both effectiveness and efficiency. Figure 9.9 graphs the calculated parameter values. The 'ideal performance line' concept is taken from Figure 8.1 and plotted at $45^0$ and with an origin point of (1.00, 1.00). This line represents the best balance between effectiveness and efficiency which is being sought by this research.

The baseline Strategy 1, with no annual investment, is both inefficient and ineffective. Strategy 2 (€545,000/ annum) is both effective and efficient from $T_0$ to $T_4$, but reduces in both effectiveness and efficiency from $T_4$ to $T_5$. Strategy 3 (€870,000/ annum), Strategy 4 (€2,000,000/ annum) and Strategy 5 (€3,000,000/ annum) are both effective and efficient between $T_0$ and $T_2$, but alternate between high and reduced effectiveness and efficiency from $T_2$ to $T_5$. As Strategies 4 and 5 are practically coincident, it can be inferred that Strategy 4 achieves, in general, the same performance as Strategy 5 with a lesser annual investment.

In terms of the 'ideal performance line', it is evident that this lies between the performances of Strategies 2 and 4. These strategies therefore represent the range of possible strategies wherein lies the optimum strategy for the given dataset.

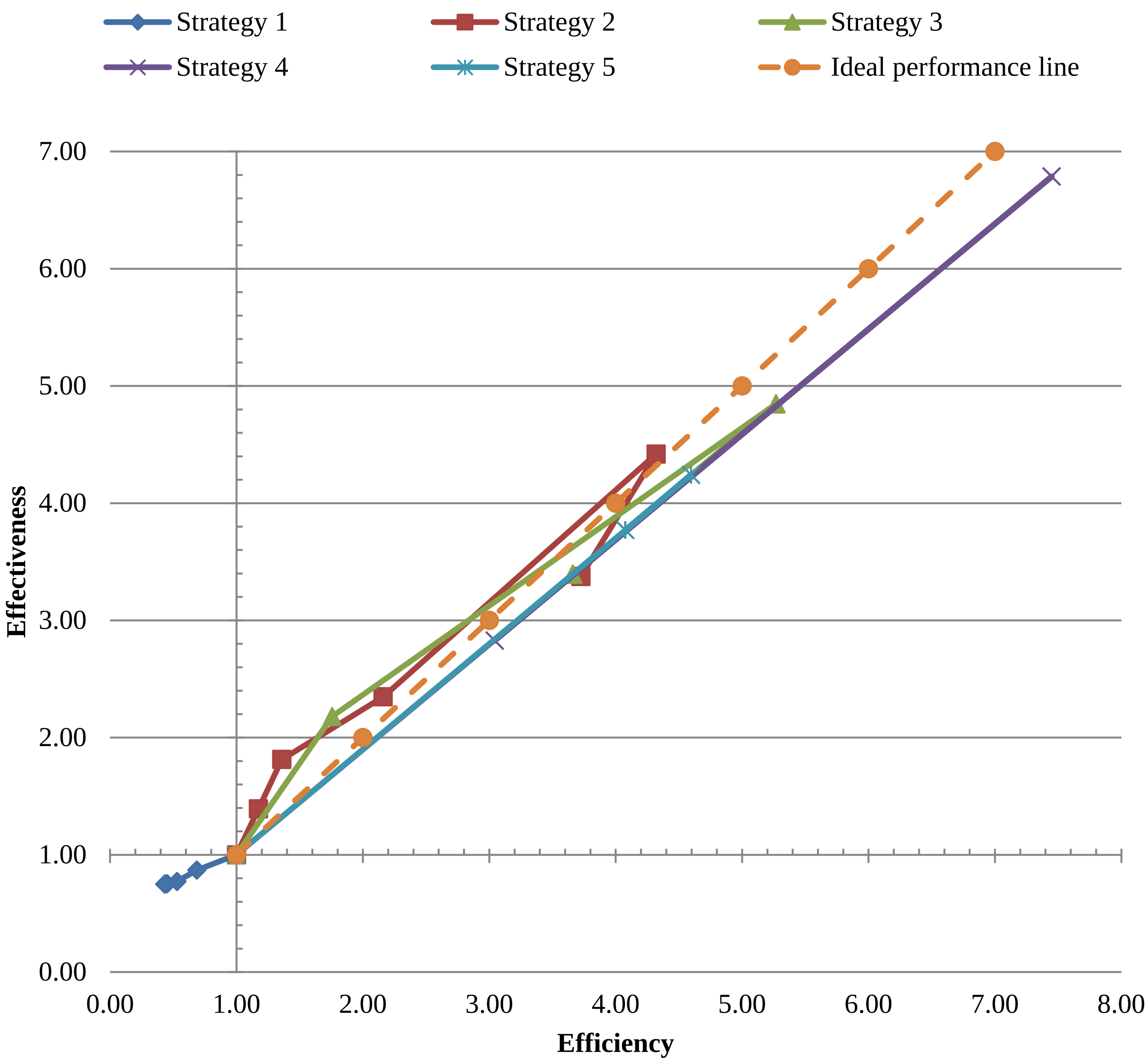



**Figure 9.9. Strategy performances.**

**(iv). Benchmark comparison.**

The strategies have been presented graphically in Figure 9.10 in terms of percentage of bridge stock replacement cost. The range between Strategy 2 (0.27%) and Strategy 4 (1%, with intermittent investment of 0.35%)) is shaded and represents the minimum and maximum value range for the optimum level of investment required in achieving full bridge network rehabilitation within the strategy time horizon and providing a minimum 85 year service life for all structures.

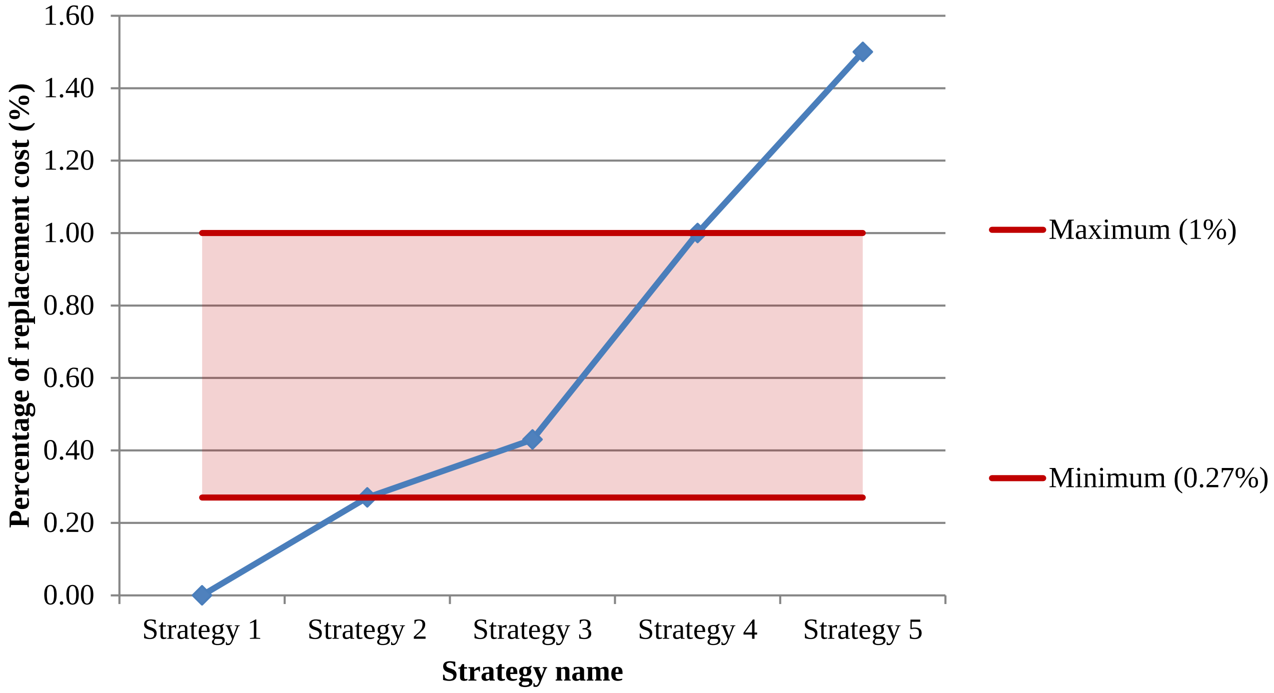



**Figure 9.10. Range of optimum level of investment in terms of strategies.**

These findings confirm the applicability of the developed methodology:

- The range between the minimum and optimum investment levels is within the reported range of international practice (0.24% to 1.79%).
- The maximum investment level of 1% lies very close to the calculated mean value of 0.92% for international practice.

## 10.0 Discussion, conclusions and recommendations for further work.

A bridge rehabilitation strategy model has been developed that assesses the overall bridge stock and optimises bridge rehabilitation strategies at a network level under the constraints of limited budgets and resources. The available dataset has been consolidated into a usable format and descriptive statistical analyses undertaken. The development of performance indicators using the effectiveness and efficiency parameters provides a unique approach to the evaluation of the success of a rehabilitation strategy. The application of this concept to the subject dataset and agreement with international practice confirms the approach taken in its formulation.

The research has led to a number of noteworthy findings:

(i). Bridge management system datasets are a valuable source of research information. This present research, which is the first systematic investigation of a regional Irish dataset, confirms the depth and breadth of the potential of BMS data for future investigation.

(ii). The study area and the available dataset are of national significance, given their relative percentage share of the State's regional and local road lengths (10.7%), river lengths (11.8%) and regional and local road bridges (7.2%). This level of significance confirms the transferability of the research findings to other road authorities in Ireland.

(iii). Data analysis has highlighted the high frequency of bridge scour in the surveyed bridges. The incidence of scour at 62%, as investigated in a sample of critical condition bridges, exceeds the range of 15% to 25% reported internationally. This finding would not have emerged without this research into the dataset.

(iv). The lack of deterioration, prioritisation and strategy optimisation modules or capabilities in the Eirspan package inhibits a full understanding of the requirements for managing the bridge network.

(v). An annual deterioration rate of 0.057 in bridge condition rating has been established; this equates to a one point reduction in rating every 17.5 years.

(vi). The research has identified that different motivations and judgements apply in the selection of rehabilitation projects for critical condition structures at or close to failure compared to non-critical structures.

(vii). For critical condition structures, the priority or sequence in which bridge rehabilitation projects were undertaken was found to be a function of the values of the overall structural condition and AADT variables, with the overall structural condition parameter being the most influential. Faced with a number of critical bridges, the calculated priority index confirms that the road authority adopted an approach based on firstly public safety and secondly on minimising disruption to heavily trafficked routes.

(viii). For non-critical condition bridges, the priority index based on identified influencing factors from a survey of experts has been found to be a function of the values of the hydraulic vulnerability, the overall structural condition, the structural non-scour and AADT variables, with their influence ranked in that order.

(ix). The standard economic appraisal method of Net Present Value has been found to have limitations in assessing a multiple project strategy such as the rehabilitation of a bridge stock, where the stock is continuously deteriorating. The NPV method does not provide a clear indication of the performance of a strategy in terms of ongoing achievement of results and does not quantify improvement in the bridge stock.

(x). The range of annual investments required to achieve full bridge network rehabilitation within the strategy time horizon and thus provide a minimum 85 year service life for all structures have been calculated as 0.27% (minimum) and 1% (maximum) respectively of the bridge stock replacement value. The current investment level of 0.43% lies within the calculated range.

(xi). The application of the performance indicators of effectiveness and efficiency, taken from UK, New Zealand and French practice, and their evaluation by the concept of system performance have been shown to be a robust assessment process methodology that is confirmed with reference to international practice.

The research suggests future work that could be undertaken on this topic:

(i). Future inspections and condition ratings of the bridges within the dataset will allow confirmation of the deterioration rate estimated in this research.

(ii). With respect to rehabilitation project costs, the absence of a significant number of actual construction cost records has led to the estimated Eirspan dataset costs only being considered in the analysis. As further projects are completed and a database of actual costs emerges, future research could focus on actual costs, which would further refine the optimisation process.

(iii). Research into bridge management systems that have deterioration, prioritisation and strategy optimisation capabilities and the incorporation of these capabilities into Eirspan BMS would benefit bridge management in Ireland.

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# Appendices

## Appendix A

Civil Engineering Research in Ireland (CERI) paper, Galway, August 2016

CERI paper, Dublin, August 2018

# An Analysis of a Data Set of 1,400 Bridge Inspections in County Cork.

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ABSTRACT: A recent project by Cork County Council has allowed the compilation and analysis of detailed inventory and inspection data of 1,400 bridges on its regional and local road network. Each bridge and its constituent components or elements have been visually inspected and their structural condition rated based on a defined scale of deterioration and damage. This paper presents data on bridge structure type and geometry as well as condition ratings for each bridge component. The worst performing bridge components and the most recurrent damage types are identified. Conclusions are drawn on the overall condition of the bridge stock, the critical structural components and the deterioration mechanisms that impact upon them.

KEY WORDS: Bridge management systems; Structural inspection; Bridge defects; Data analysis.

## 1 INTRODUCTION

The National Roads Authority (now Transport Infrastructure Ireland) has developed Eirspan as the Irish bridge management system [1]. Between 2012 and 2014, Cork County Council undertook a survey of bridges on regional and strategic local roads. The survey process comprised two distinct stages:

(i). Bridge inventory collection where the name, location, type and geometry of the bridge stock are recorded and collated. For each structure, up to 58 separate parameters were recorded.
(ii). Principal inspection where the damage type is recorded and a condition rating value is assigned to the constituent components and the overall bridge structure. For each structure, up to 21 separate parameters were recorded.

The survey has thus yielded an extensive and detailed database of over 100,000 separate pieces of empirical information. To date, no analysis of bridge typology and physical condition based on this quantity of data has been undertaken on a regional Irish bridge stock. The available data set of inventory and principal inspection records provides an opportunity to undertake such an exploratory analysis.

This paper describes the findings of the analysis and how the findings improve the understanding of the performance of the bridge stock. The scope of the study consists of data integration, summary and descriptive statistics, and the interpretation of results. The objectives of this study are to compile and consolidate the available data set into a usable tabular format and extract information to discover previously unknown patterns, trends and relationships within the data.

The study has established the characteristics of the bridge stock in terms of geometry and condition ratings. The bridge components most susceptible to damage have been identified and a Pareto analysis has determined the most frequent types of damage that have impacted upon the bridges and their constituent elements. The cost of rehabilitation in terms of components and condition ratings has been determined.

## 2 METHODOLOGY

The data set of the bridge survey observations has been generated by the Eirspan system in 'Notepad' format. Notepad is a plain text (i.e. data) editor for Microsoft Windows and is a basic text editing program that enables the creation of documents. The Notepad data files were imported into a Microsoft Excel spreadsheet where the data were sorted and checked for errors and inconsistencies. The Microsoft Excel spreadsheet provides a computer application for the organisation, analysis and storage of the data in tabular format

The dataset, now in tabular spreadsheet format, has been manipulated and analysed and the results of queries undertaken form the basis for this paper.

## 3 BRIDGE TYPOLOGY

The database has records of 1,367 bridges, of which 435 were on regional roads and 932 were on strategic local roads.

### 3.1 Geometry

Of the surveyed bridges, 1,244 (91%) have three spans or less as shown in Figure 1.

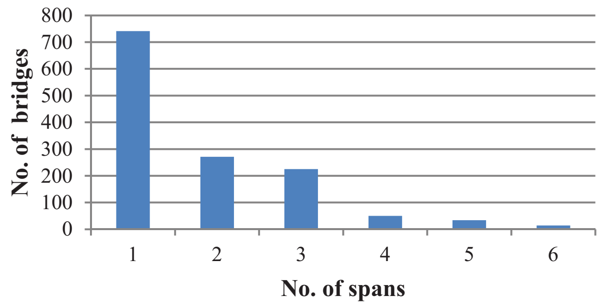


Figure1. Number of spans of surveyed bridges.

With respect to span lengths, 1,094 (80%) of bridges have span lengths no greater than 6m as shown in Figure 2.

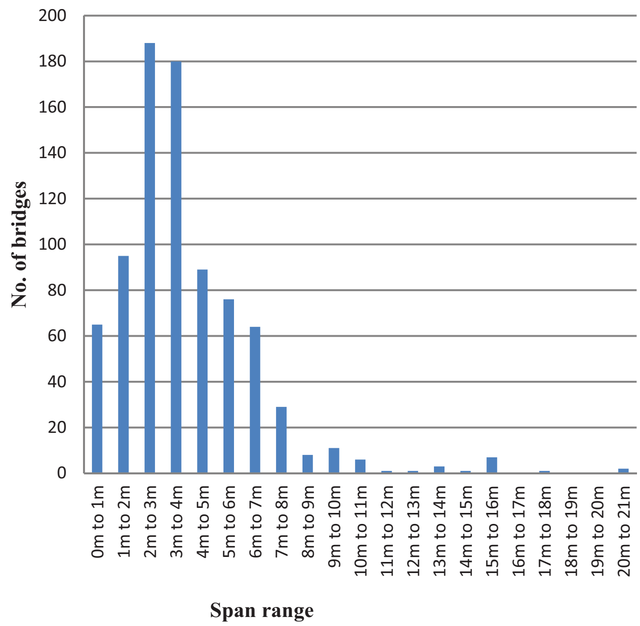


Figure 2. Range of span lengths of surveyed bridges.

The bridge out-to-out width, which is defined as the total width of the superstructure, is measured perpendicular to the bridge span [2]. Given that the surveyed bridges are on predominantly two-lane roadways, 1,148 (84%) have measured out-to-out width values less than 10m as shown in Figure 3.

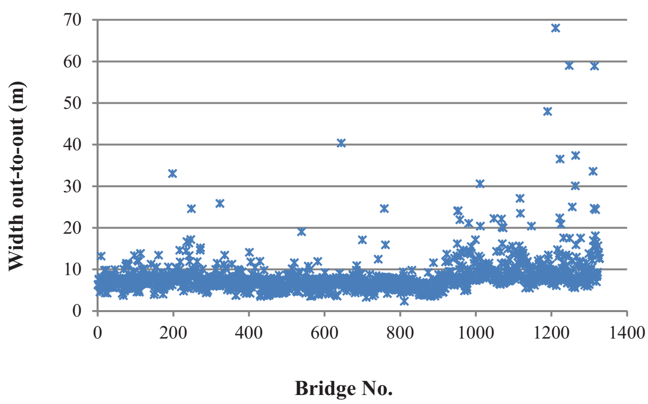


Figure 3. Out-to-out widths of surveyed bridges.

### 3.2 *Superstructure types*

The Eirspan system records the superstructure parameters by using a standard list of element descriptions. These records have been analysed and assessed to provide a fuller interpretation of the data set.

The parameter 'design of elevationof superstructure' describes the elevation, or longitudinal layout, of the superstructure.The most common types of superstructure elevation identified are the 827 (60.5%) 'arches of one or more spans' bridges and the 410 (30%) 'simple span, constant cross-section' bridges as shown in Figure 4. These two main types have been further investigated in terms of construction material. In the case of arches, 783 (94.7%) are of stone masonry (Figure 5), while for simple spans of constant cross-section, 223 (54.4%) are of in-situ reinforced concrete and 97 (23.7%) are of stone masonry (Figure 6). This masonry material may be explained by the presence of 'clapper' bridges, which are large flat stone slabs supported on piers and abutments. In the data set, these bridges have a span range between 0.5m to 2.1m, with an average span of 0.9m. An example is shown in Figure 7.

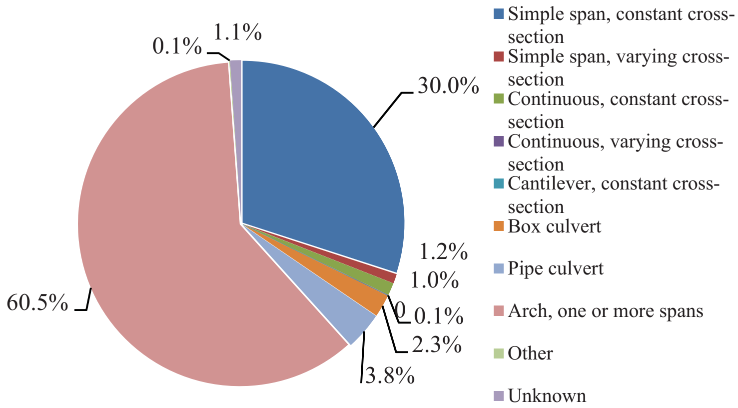


Figure 4. Design of elevation of superstructure.

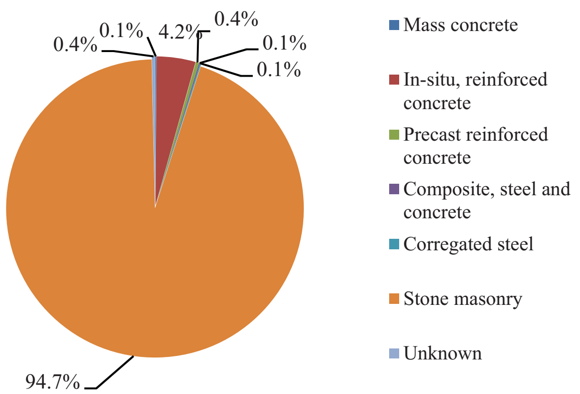


Figure 5. Construction materials of arches.

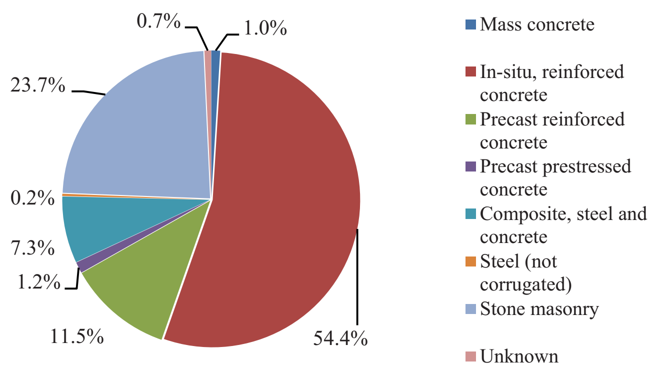


Figure 6. Construction materials of simple spans of constant section.

Figure 7. Typical ‘clapper’ bridge deck arrangement.

### *3.3 Substructure types*

As in the case of the bridge superstructure, Eirspan records the substructure parameters by using a standard list of descriptions. The results of the analysis of the data for abutment type and material are presented in Figures 8 and 9.

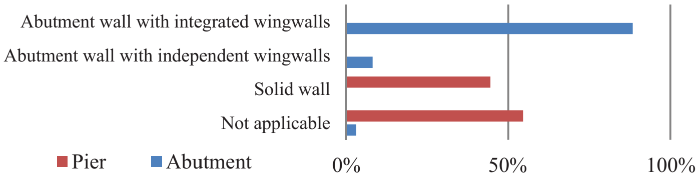


Figure 8. Abutment and pier type.

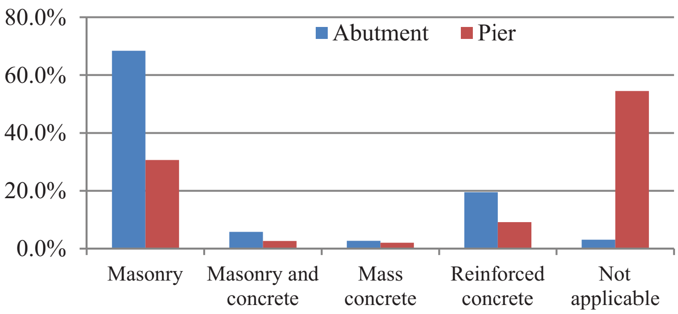


Figure 9. Abutment and pier material.

## 4 BRIDGE COMPONENT AND OVERALL STRUCTURE CONDITION RATINGS.

The Eirspan system [3] describes the inspection process as:

> *“a systematic visual check of all accessible parts of the structure......these purposes are fulfilled by:*
> - *a condition rating of the structure and each of its components.*
> - *registering the type and extent of any significant damage”.*

The condition rating for both the bridge components and the overall structure is a value between ‘0’ and ‘5’ (as well as ‘?’ and ‘-‘).These rating values are defined in Table 1.

Table 1. Eirspan condition ratings.

| Condition Rating | Definition |
|---|---|
| 0 | No or insignificant damage. |
| 1 | Minor damage but no need of repair. |
| 2 | Some damage, repair needed. |
| 3 | Significant damage. |
| 4 | Damage is critical. |
| 5 | Ultimate damage. |
| ? | Unknown. |

Eirspan [3] defines a total of 13 bridge components and the condition rating of the overall structure is determined by the individual ratings of five ‘critical’ components, which have been defined as ‘Abutments’, ‘Piers’, ‘Bearings’,‘Deck/Slab’ and ‘Beams/Girders/Transverse beams’.

### *4.1 Overall structure ratings of surveyed bridges*

From the analysis of the data, the percentage of bridges in terms of overall condition rating has been derived and is presented in Figure 10. In descending order they are 732 (53.5%) rated Condition 2, 272 (19.9%) rated Condition 3, 181 (13.2%) rated Condition 1, 81 (5.9%) rated Condition 4, 34 (2.5%) rated Condition 0 and 30 (2.2%) rated Condition 5.

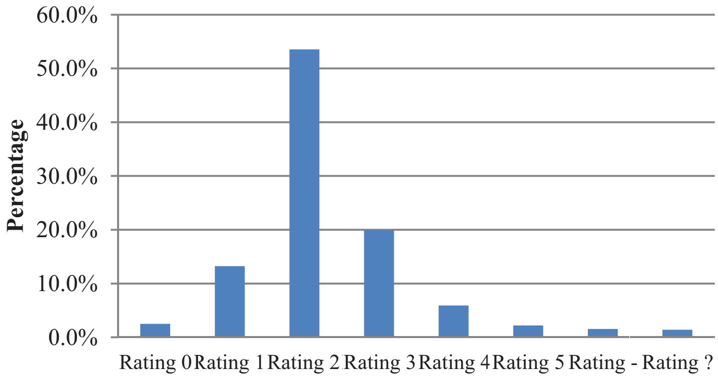


Figure 10. Overall structure ratings of bridge stock.

### *4.2 Critical component condition ratings*

The component rating data have been analysed to identify the critical components, which determine the overall structure ratings; these are shown in Figure 11 for overall structure ratings ‘5’ to ‘2’.

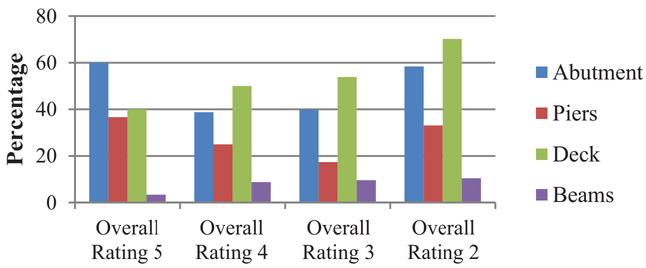


Figure 11. Percentage of critical component ratings at overall structural rating.

## 5 DAMAGE TYPES

The Eirspan system records damage type by using a standard list of descriptions [3]. These records have been analysed and the results assessed.

In the consideration of damage types or defects within systems or processes, Montgomery [4] describes the Pareto analysis methodology, which consists of identifying quality issues by category or by type of defector nonconformity. This analysis is based on the ‘Pareto Principle’, also known as the 80/20 Rule, which is a method of identifying issues that impact upon process performance and quality control [5]. It is attributed to the work of Italian economist Vilfredo Pareto, who observed that in the early 20th Century, 80% of the wealth in his country was owned by 20% of the population. It has been generalised to mean that approximately 80% of any given effect can be attributed to 20% of the possible causes. Conversely, the remaining 80% of causes account for only 20% of the effects.

The output from this analysis may be presented in a Pareto chart, which is a frequency distribution of attribute data arranged by category. For the recorded bridge data, the damage types for each component have been analysed in Pareto chart format for each of the critical components in Figures 12-15 and the ‘80% damage types’ for each component are presented in Table 2.

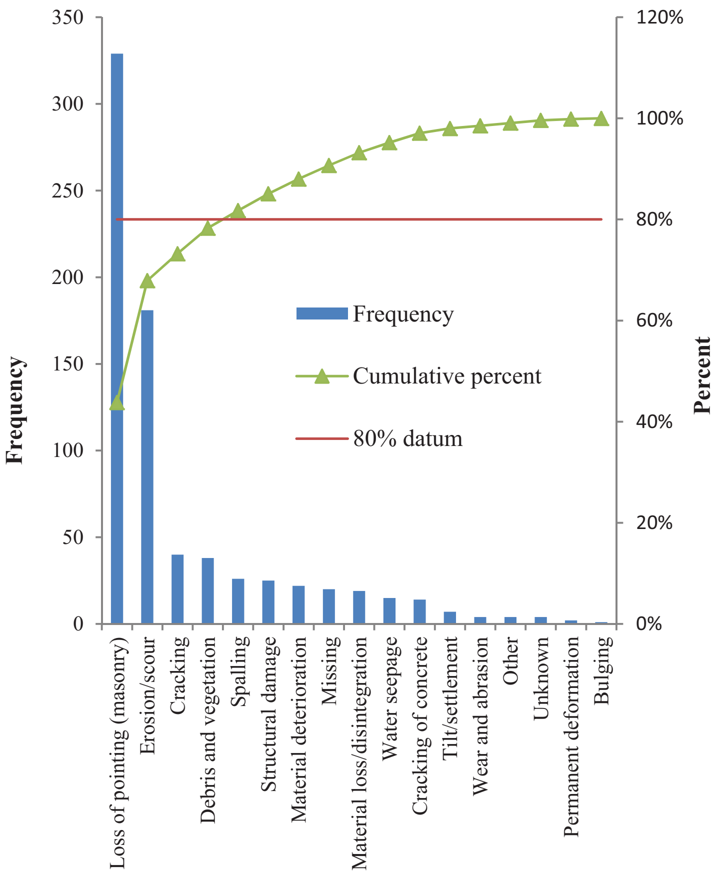


Figure 12. Pareto chart for damage to abutments.

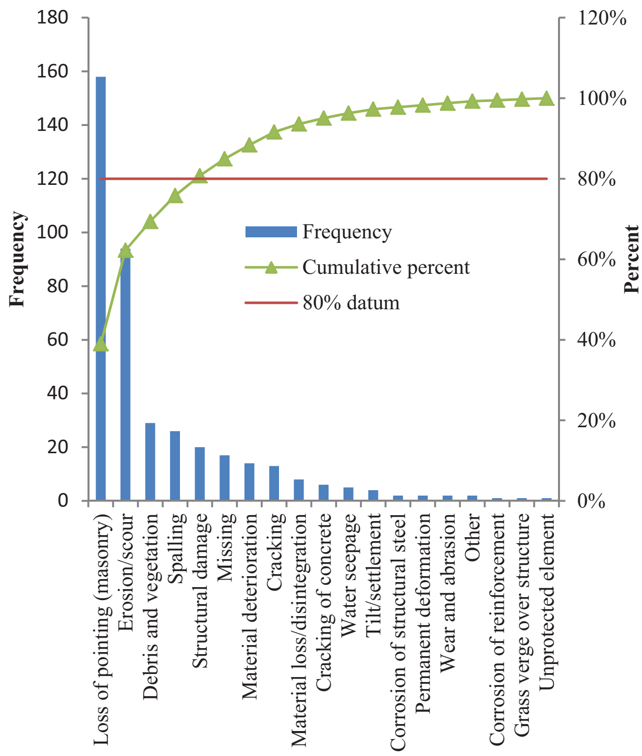


Figure 13. Pareto chart for damage to piers.

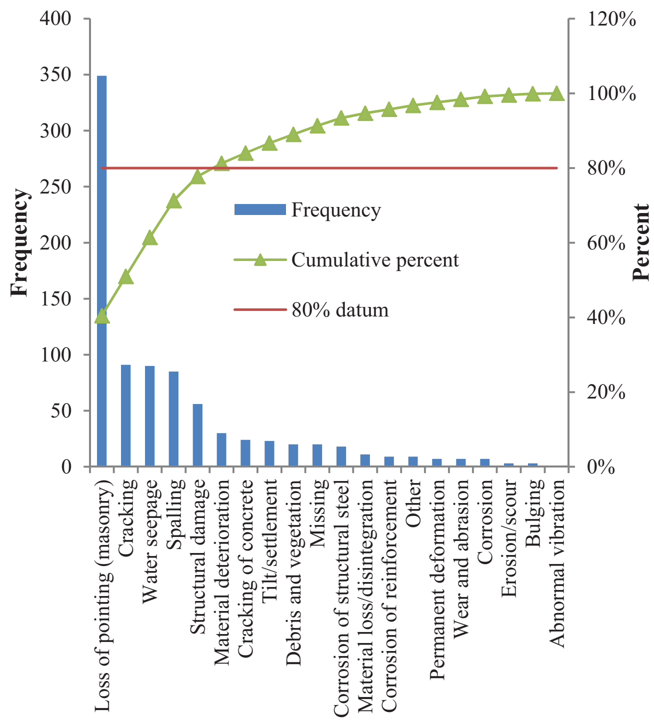


Figure 14. Pareto chart for damage to deck/slab.

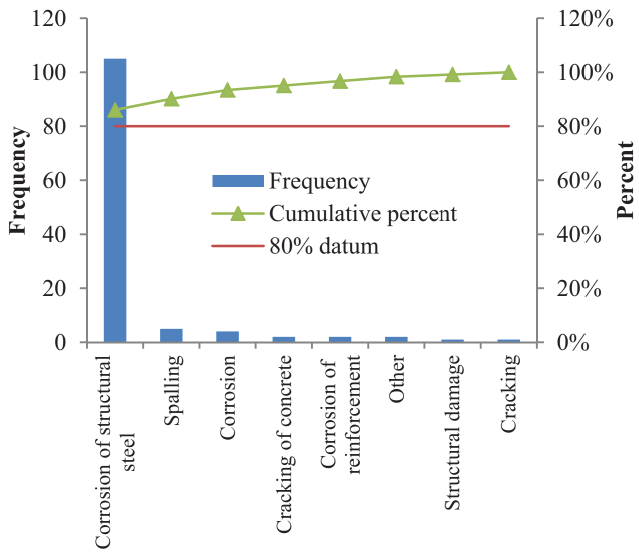


Figure 15. Pareto chart for damage to beams/girders/transverse beams.

Table 2. Most frequent types of damage.

| Component Name | Most frequent types of damage |
|---|---|
| Abutments | • Loss of pointing (masonry)<br>• Erosion/scour<br>• Cracking<br>• Debris and vegetation |
| Piers | • Loss of pointing (masonry)<br>• Erosion/scour<br>• Debris and vegetation<br>• Spalling |
| Deck/slab | • Loss of pointing (masonry)<br>• Cracking<br>• Water seepage<br>• Spalling<br>• Structural damage |
| Beams/girders/ transverse beams | • Corrosion of structural steel |

Examples of component condition ratings from the data set are shown in Figures 16-18.

Figure 16. Intermediate pier component rated condition ‘5’ in a structure with an overall condition rating of ‘5’.

Figure 17 .Deck (arch barrel) component rated condition ‘5’ in a structure with an overall condition rating of ‘5’.

Figure 18. Abutment component rated condition ‘5’ in a structure with an overall condition rating of ‘5’.

## 6 BRIDGE STOCK REHABILITATION COST

Analysis of the data set shows that the total cost for the rehabilitation of the bridge stock is €24.4 million. This has been further investigated as shown in Figures 19 and 20. In terms of bridge components, bridge surfaces at €4.9 million are the largest cost followed by bridge decks at €4.7 million.With regard to condition ratings, Condition 2 rated bridges at €16.4 million are the largest cost followed by Condition 3 rated structures at €3.9 million.

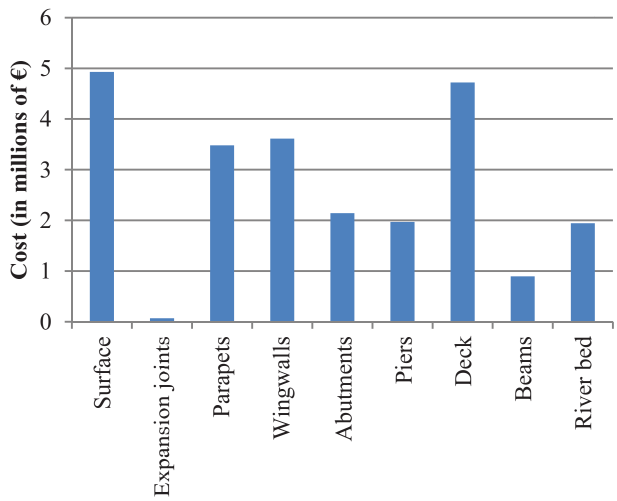


Figure 19. Rehabilitation costs in terms of bridge components.

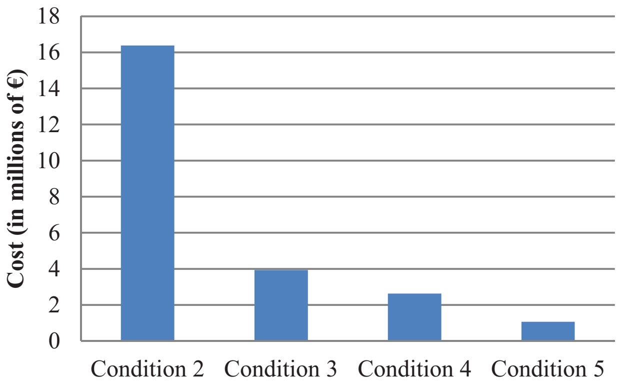


Figure 20.Rehabilitation costs in terms of overall bridge condition ratings.

## 7 SUMMARY

Research thus far has determined that the surveyed bridge stock may be described as being predominantly of structures having less than three spans with the majority of span lengths being less than 6m and with the out-to-out widths of the structures being predominantly less than 10m.

In terms of bridge superstructure cross-section and material, in excess of 60% of the structures are arches of one or more spans, followed by simple span bridges of constant cross-section at 30%. The arch bridges are overwhelmingly of masonry construction while the simple span arrangements are mainly of either in-situ reinforced concrete or masonry. For the bridge substructures, abutments primarily consist of masonry walls with integrated wingwalls. Intermediate pier information is not as complete as that available for abutments.

With regard to the overall condition of the surveyed bridge stock, 28% have suffered at least significant damage while 81% have suffered at least some damage.

The worst performing components for structures with an overall condition rating of ‘5’to ‘2’ have been found to be the abutments and deck.

As part of the investigation of the data, a Pareto analysis of the reported damage types has been undertaken for the ‘critical’ components. For the abutments, the most frequent types of damage are loss of pointing (masonry), erosion/scour, cracking and debris/vegetation. In the case of piers, the most frequent are the loss of pointing (masonry), erosion/scour, debris/vegetation and spalling. For the deck/slab component, the most frequent are the loss of pointing (masonry), cracking, water seepage, spalling, and structural damage, while for the beams/girders/transverse beams component, the main damage types are corrosion of structural steel.

With respect to cost, the overall rehabilitation cost for the surveyed bridge stock is €24.4 million. In terms of bridge components, bridge surfaces are the largest cost followed by bridge decks. In the case of condition ratings, Condition 2 rated bridges form the largest cost followed by Condition 3 rated structures.

The approach taken in this study has shown that the data set is a valuable resource of empirical data, the analysis of which leads to a better understanding of the characteristics and performance of the bridge stock. The critical bridge components have been verified and an analysis of the damage types has established that a small number of physical processes are responsible for the majority of bridge component deteriorations. The consideration of rehabilitation costs provides an insight into the scale of the task of managing the bridge stock.

The results of this study allow a better understanding of the deterioration factors impacting upon the bridge stock and thus improve the prediction of future bridge conditions and enhance decision making with respect to the allocation of resources.

## 8 FURTHER RESEARCH

The intended outcome of future research is the development of an integrated bridge prioritisation index as a decision making aid in the targeted allocation of resources for the rehabilitation of bridges on a regional road network. The research will build upon the work of Valenzuela et al. [6] on bridges on the Chilean road network. The proposed index will consider the structural condition, hydraulic vulnerability, repair cost and strategic importance of individual bridges on the network. It is proposed that the index will be calibrated by a review of bridge rehabilitation projects already undertaken in County Cork, by a survey of experts in the fields of bridge design and construction, bridge maintenance and bridge inspection; and by further in-depth statistical analysis of the data.

## ACKNOWLEDGMENTS

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# A bridge rehabilitation strategy based on the analysis of a dataset of bridge inspections in Co. Cork.

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ABSTRACT: A bridge management system (BMS) allows bridge owners assess the condition of their bridge stock and formulate bridge rehabilitation strategies under the constraints of limited budgets and resources. This research presents a decision-support system for bridge managers in the selection of the best strategy for bridge rehabilitation on a highway network. The basis of the research is an available data set of 1,367 bridge inspection records for County Cork that have been undertaken to the Eirspan BMS inspection standard. A procedure proposed by previous research on the prioritisation of theoretical bridge rehabilitation projects on the Chilean road network has been built upon and statistical analysis of both recent rehabilitation projects in County Cork and of a survey of expert practitioners has established separate project prioritisation indices for critically and non-critically damaged structures. A deterioration rate which predicts the annual disimprovement in condition rating of each bridge has been calculated using statistical regression analysis and provides a basis for the estimation of investment requirements for an overarching rehabilitation strategy. A system performance method developed by this research and which uses efficiency and effectiveness indicators taken from UK, New Zealand and French practice has determined that minimum and optimum annual investment amounts equivalent to 0.27% and 1% respectively of the bridge stock replacement cost are required to achieve full bridge network rehabilitation and provide a minimum 85 year service life for all structures. A benchmarking comparison with reported international practice has confirmed the applicability of the developed methodology.

KEY WORDS: Bridge management systems; project prioritisation; deterioration rate; system performance indicators.

## 1 INTRODUCTION

Highway bridges experience deterioration due to natural hazards, ageing, and increased structural performance demands. In a climate of scarce financial resources, managers of highway bridges face challenges in maintaining a safe and efficient network and have to be effective in their management strategies. A bridge network is an integral part of the transportation infrastructure and typically comprises about 2% of a road network's length and about 30% of its value [1].

Due to their critical function, partial or total bridge closure can result in major disruption such as long diversions, congestion and even the total isolation of certain areas. The challenge in bridge management is to ensure that all bridges in a network remain fit for purpose over their service life at a minimum lifecycle cost.

A recently available data set of 1,367 Eirspan bridge management system (BMS) inventory and principal inspection records provides the opportunity of an in-depth analysis of a regional bridge stock with a rehabilitation cost estimate of €24.2 million and where 26% have suffered at least significant damage and 86% have suffered at least some damage. The Eirspan system, in common with many other bridge management systems [2], does not predict bridge deterioration rates or determine the best intervention or rehabilitation strategies.

The purpose of this research is the development of a bridge rehabilitation strategy model as a decision making aid to bridge owners. The research recognises the decision problems faced by the bridge owner with respect to the requirement for the prioritisation of rehabilitation projects, the uncertainty of the future deterioration of bridges and the limitations of funding resources.

## 2 FORMULATION OF BRIDGE REHABILITATION STRATEGY

The formulation of the rehabilitation strategy follows the sequential process outlined in this Section.

### *2.1 Eirspan BMS and data compilation*

The National Roads Authority (now Transport Infrastructure Ireland) developed Eirspan, which is a customised version of the Danish DANBRO system, in 2001 as the Irish bridge management system [3] Between 2012 and 2014, Cork County Council undertook a survey of 1,367 bridges on regional and strategic local roads.

Eirspan describes each structure in terms of 13 individual bridge components. The 'condition rating' system for the individual components is assigned by the trained bridge inspector and is a six point system (ranging from '0' to '5') defined in Table 1.

Table 1. Eirspan condition ratings [4].

| **Condition Rating** | **Definition** |
|---|---|
| 0 | No or insignificant damage |
| 1 | Minor damage |
| 2 | Some damage, repair needed |
| 3 | Significant damage |
| 4 | Damage is critical |
| 5 | Ultimate damage |

The condition rating of the overall structure is determined by the highest rating of five ‘critical’ components (piers, abutments, bearings, deck and beams). A module within the Eirspan database provides a cost estimate for the rehabilitation of each structure.

The dataset of the 1,367 bridge records was generated by the Eirspan BMS in ‘Notepad’ format. Notepad is a plain text (i.e. data) editor for Microsoft Windows and is a basic text editing program that enables the creation of documents. The Notepad data files were imported in a comma-separated value (CSV) format into Microsoft Excel and converted into a spreadsheet format, where these data was sorted and checked for errors and inconsistencies. The SPSS data analysis package was used for advanced descriptive, inferential and predictive statistical analyses.

### *2.2 Deterioration model for bridge structures*

The rate of deterioration predicts the future condition or performance of an asset if no maintenance, rehabilitation or improvement is undertaken. If both the current condition and deterioration rate is known, the remaining period of time in which the asset satisfies all of its functional requirements may be estimated.

This research used a deterministic model approach where statistical analysis was undertaken on published bridge life expectancy values for European bridge stocks [5,6] with similar characteristics. Using SPSS data analysis software, a simple linear regression analysis established a significant relationship between the overall bridge condition and age ($R^2 = 0.949$, $F(1,97) = 1818.75$, $p < 0.001$) and generated regression equation (1):

$$Condition\,rating = 0.16 + 0.057\,(Age) \qquad (1)$$

where Condition rating is measured on the 6-point Eirspan scale and Age is measured in years. The bridge condition rating value thus increases by 0.057 every year i.e. there is a one point increase in condition rating every 17.5 years. The adjusted R squared value indicated that approximately 95% of the variation in ‘Condition Rating’ scores was predicted by the ‘Age’ scores.

### *2.3 Prioritisation model for bridge rehabilitation projects*

Ranking and prioritisation procedures are widely used by transportation agencies to evaluate and select bridge projects [7]. The principal of a prioritisation model or index is to rank the bridges for rehabilitation priority based on characteristic attributes, such as:

- the importance of a bridge on a road network, which may be described in terms of criteria such as road category, annual average daily traffic or detour distance, and
- an assessment of the bridge condition, which may be expressed by parameters such as structural stability, remaining life or general condition.

The general form of a priority index [8] is:

$$PI = \sum_{i=1}^{i=n} K_i f_i\,(a, b, c \,\ldots.) \qquad (2)$$

where PI is the maintenance priority index; $K_i$ are the weighting factors for each criterion considered; $f_i\,(a, b, c, \ldots)$ are priority ranking formulas; and a,b,c... are the bridge attributes or parameters.

Bridge maintenance priority indices have been the focus of previous research internationally using a range of parameters:

- load capacity, remaining life, deck width, horizontal and vertical clearances have been used by different States in the USA for the development of ranking formulae [8].
- in Greece, structural defects, traffic volume, environmental conditions, bridge age, river bed characteristics and foundation and superstructure type have been used [9] for developing a priority index.
- research in Vietnam [10] has taken into consideration structural condition, location, width, traffic volumes and budget constraints for the determination of bridge importance.
- an index for bridges on the Chilean road network [11] considered the annual average daily traffic, length and width of bridges, availability of alternative routes, social and economic development of the area and load restrictions.
- in Australia, research [12] investigated the structural condition of bridge components, the vulnerability and location of the bridge, bridge age, road classification, number of lanes, the width of the deck, vertical clearance and the social implications of rehabilitation in the development of a ranking method.

For this research, ten parameters or influencing factors, based on previous research and shown in Table 1, were identified. Each parameter was in turn divided into interval categories, for example, Average Annual Daily Traffic (AADT) was given the following interval values:

1. AADT < 1,000
2. 1,000 < AADT < 3,000
3. 3,000 < AADT < 10,000
4. AADT < 10,000

Table 1. Influencing factors.

| Number | Parameter | Number | Parameter |
|---|---|---|---|
| 1 | Average Annual Daily Traffic | 6 | Bridge material type |
| 2 | Availability of alternative route | 7 | Number of spans |
| 3 | Bridge type | 8 | Rehabilitation cost |
| 4 | Hydraulic vulnerability | 9 | Road classification |
| 5 | Overall structural condition | 10 | Structural non-scour condition |

Previous research on bridges on the Chilean road network [11] proposed a methodology for the formulation of a prioritisation index for bridge rehabilitations.

This present research recognises that different motivations and judgements apply in the selection of rehabilitation projects for critically damaged structures at or close to failure (condition rating 5 ‘ultimate damage’ and condition rating 4 ‘damage is critical’) compared to non-critically damaged structures (condition ratings 3 ‘significant damage and condition rating 2 ‘significant damage).

There are therefore two prioritisation indices established:

(i). A prioritisation index for critical condition bridges.

The highway authority undertook the rehabilitation of 37 condition rated 4 and 5 bridges in 2014 and 2015. These projects were deemed to be the most urgent and received funding priority. The details of 37 rehabilitation projects in the study area were reviewed and listed in their order of undertaking (priority number).

Multiple regression analysis was conducted using SPSS statistical software on the data sample ($n = 37$) to establish the best combination of independent variables that predicted the dependent variable (the priority number). The prediction model contained two of the ten predictors and was reached in two steps, with six outliers removed. The analysis produced a significant regression equation ($R^2 = 0.905$, $F(2,28) = 133.938$, $p < 0.001$). The adjusted $R^2$ value indicated that approximately 90% of the variation in the priority number may be predicted from the derived regression equation:

$$PI = 127.51 - 21.91\,(OSC) - 5.59\,(AADT) \quad (3)$$

where PI is the priority index; OSC is the overall structural condition and AADT is the annual average daily traffic.

(ii). A prioritisation index for non-critical condition bridges.

A survey panel of 33 experts were asked to rate in a questionnaire the order of precedence of the ten stated influencing factors. A total of 23 (70%) responses were received. The experts were asked to rank the factors in order of importance. The results from each respondent were processed by assigning a value of ‘10’ to the first factor, ‘9’ to the second factor and so on. These survey results were then tested for normality using SPSS software. Shapiro-Wilks tests ($p>0.05$) and a visual inspections of their histogram, normal Q-Q plots and box plots showed that seven of the ten factors were not normally distributed and, to provide a robust measure of central tendency, the median values were used to rank in order of priority the results obtained from the analysis, which are shown in Table 2.

Table 2. Ranked influencing factors from expert survey.

| Ranking | Factor | Median value | Interquartile range |
|---|---|---|---|
| 1 | Overall structural condition | 10 | 1 |
| 2 | Hydraulic vulnerability | 9 | 1 |
| 3 | Structural non-scour condition | 8 | 1 |
| 4 | Average Annual Daily Traffic | 6 | 2 |
| 5 | Availability of alternative route | 6 | 3 |
| 6 | Rehabilitation cost | 5 | 2 |
| 7 | Road classification | 5 | 3 |
| 8 | Number of spans | 3 | 2 |
| 9 | Bridge material type | 2 | 1 |
| 10 | Bridge type | 2 | 2 |

Using the SPSS package, a randomised sample (*n* =115) of non-critical condition 2 and condition 3 bridges was generated and then sorted in Microsoft Excel, using the precedence ranking of the influencing factors from the expert survey to form a prioritised list.

A multiple regression analysis, using the stepwise method, was conducted using SPSS on the data sample to establish the best combination of independent variables that predict the dependent or predicted variable, the priority number. The prediction model contained six of the ten predictors and was reached in six steps, with seven outliers removed. The analysis produced a significant regression equation ($R^2 = 0.950$, $F(6,107) = 319.48$, $p < 0.001$). The adjusted $R^2$ value indicates that approximately 95% of the variation in the priority number may be predicted from the derived regression equation:

$$PI = 216.66 - 29.44\,(HY) - 22.01(OSC) - 13.43(SNS) - 6.92\,(AR) - 6.75\,(AADT) - 2.09\,(RC) \quad (4)$$

where PI is the priority index, HY is hydraulic vulnerability, OSC is overall structural condition, SNS is structural non-scour, AR is alternative route availability, AADT is annual average daily traffic and RC is road classification.

The derived indices are applied to the entire dataset and all projects are thus ranked in terms of priority.

### 2.4 *Performance model*

Performance measurement is a fundamental principle of management and, within the bridge management process, the identification of rehabilitation strategies is more effective when developed in a uniform and repeatable manner. The use of performance indicators improves the planning of bridge maintenance strategies [13]. For this research, the performance indicators of ‘effectiveness’ and ‘efficiency’, and their combination in terms of ‘performance’, shown in Figure 1, are considered in the assessment of strategy options and used to identify the optimal bridge stock rehabilitation strategy.

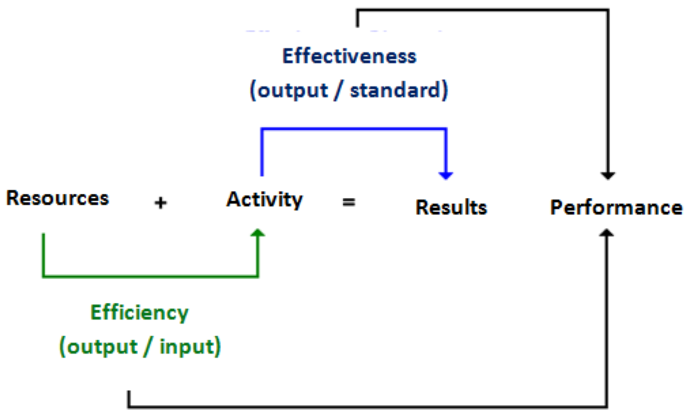


Figure 2. Efficiency, effectiveness and performance (adopted from [14]).

A six step sequential process has been used in the development of the performance model.

(i). Definition of strategy time horizon.
Based on the calculated deterioration rate, a strategy time horizon of 85 years was defined, which is equivalent to the transition time required for a bridge condition rated 0 to deteriorate, without rehabilitation, to a condition rated 5 structure i.e. the strategy time horizon is made up of five separate planning periods of 17 years, with strategy commencement at $T_0$ and five separate planning periods concluding at $T_1$ (17 years), $T_2$ (34 years), etc. This is in line with the 15 to 20 year planning period recommended for transportation projects [15].

(ii). Development of rehabilitation strategies.
Maintenance and rehabilitation practices for large asset networks are typically expressed by the ratio of annual maintenance expenditures to the estimated replacement costs [16]. In the United States, the federal government recommends that the annual maintenance and repair budgets for infrastructure assets should be set at approximately at 2% to 4% of the current replacement value [17]. In the case of bridge stocks, a review of international practice indicates that actual investment is much lower than these recommended values. Figure 3 shows the reported values, which range from 0.24% in Italy to 1.79% in Sweden and have a mean value of 0.92%.

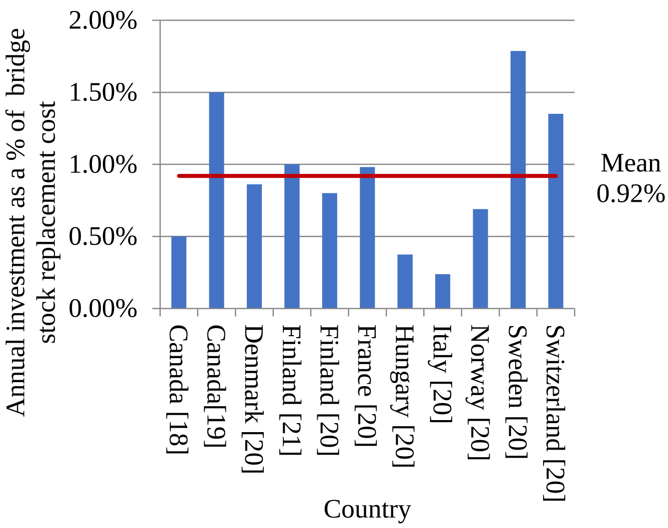


Figure 3. International annual investment in bridge stock rehabilitation.

For this research, five strategies were developed, which range from a no-investment scenario to the value range of investment levels reported in international practice and expressed in terms of the current replacement value.

- Strategy A (€0/annum). All bridges deteriorate to condition 5 at the end of 85 years.
- Strategy B (€545,000/annum): The minimum annual investment required to achieve rehabilitation of all structures within the strategy time horizon has been calculated as €545,000. Full rehabilitation is achieved at 81 years and there was an average of 17 projects per annum. This represents an annual investment of 0.27% of the bridge stock replacement cost.
- Strategy C (€870,000/annum): This is the existing strategy and represents an annual investment of 0.43% of the bridge stock replacement cost. All structures are rehabilitated to condition rating 0 at the end of 27 years and there was an average of 51 projects per annum.
- Strategy D (€2,000,000/annum): This represents an annual investment of 1% of the bridge stock replacement cost and all structures are rehabilitated to condition rating 0 at the end of 12 years. There was an average of 115 projects per annum.
- Strategy E (€3,000,000/annum): This equates to an annual investment of 1.5% of the bridge stock replacement cost and all structures are rehabilitated at the end of 8 years. There was an average of 173 projects per annum.

(iii). Assessment of strategy effectiveness.
Effectiveness is defined as the "extent to which planned activities are realised and planned results are achieved" [22]. It is thus a measure of the outcome of a strategy and can be described as the ratio of realised achievement and the planned target. This research uses the Bridge Stock Condition Index (BSCI) concept of a single numerical value to describe the condition of a bridge stock, described by the UK County Surveyors Society [23], as the measure of effectiveness. The BSCI is calculated using Equation 5.

$$BSCI = \frac{\sum_{i=1}^{i=n}(BCI\ x\ Deck\ area)}{\sum_{i=1}^{i=n} Deck\ area} \qquad (5)$$

An increase in the BSCI following the implementation of a rehabilitation strategy shows measurable effectiveness, while a decrease shows ineffectiveness. Effectiveness is calculated as the ratio of the BSCI at the start of the strategy ($T_0$) to the BSCI at the start of each planning period ($T_1$, $T_2$, etc) and the results are shown in Figure 4.

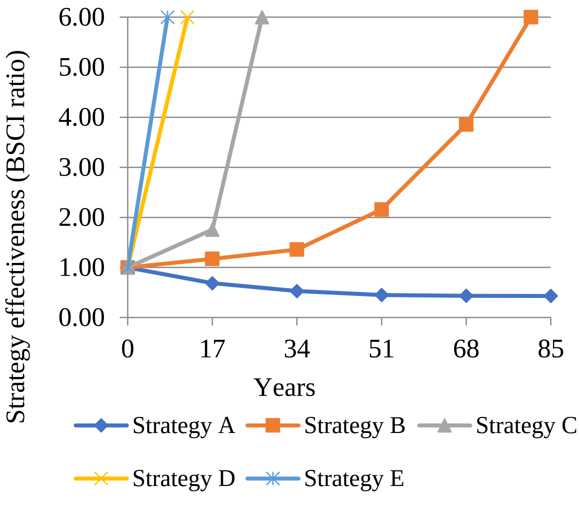


Figure 4. Strategy effectiveness.

(iv). Assessment of strategy efficiency.

The term ‘efficiency’ is reported as the “relationship between the result achieved and the resources used” [22]. It is thus a measure of economic cost and can be described as the ratio of a defined objective realised and the resources required in achieving this objective. The efficiency concept in the formulation of a bridge stock rehabilitation strategy has been applied to bridges on the French national route system [24], based on the rationale that the total bridge stock rehabilitation cost indicates the efficiency of a rehabilitation strategy. A similar approach is used by the New Zealand Transport Agency, who measures the residual asset value of their road infrastructure by the cost of its restoration [25].

Efficiency is calculated as the ratio of the total rehabilitation cost value at the start of the strategy ($T_0$) to the total rehabilitation cost value at the start of each planning period ($T_1$, $T_2$, etc) and the results are shown in Figure 5.

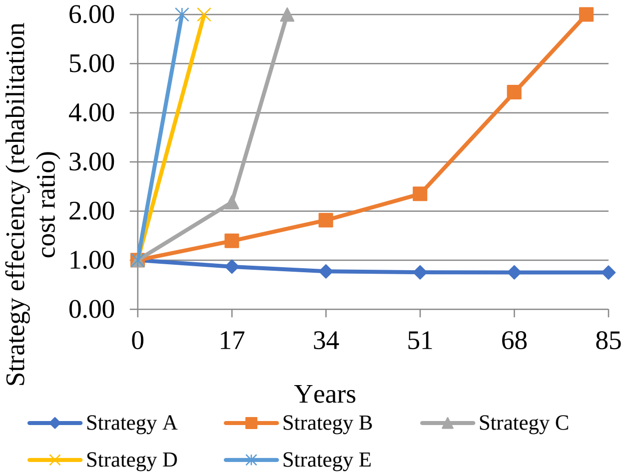


Figure 5. Strategy efficiency.

(v). Evaluation of strategy performance.

Strategy performance is evaluated in terms of both effectiveness and efficiency and Figure 6 graphs the calculated parameter values.

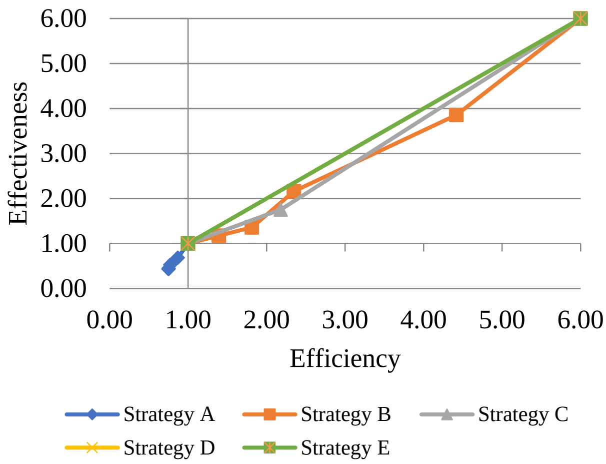


Figure 6. Strategy performance.

The baseline strategy A, with no annual investment, is both inefficient and ineffective. Strategy B (€545,000/ annum) is inconsistent and veers between high effectiveness and low efficiency and low effectiveness and high efficiency. Strategy C (€870,000/ annum) is both effective and efficient but to a lesser extent than Strategies D (€2,000,000/ annum) and E (€3,000,000/ annum). Both of these strategies are coincident and achieve full rehabilitation in the first planning period of the strategy time horizon. It can be therefore be inferred that strategy D achieves the same performance as strategy E with a lesser annual investment and may be described as the optimum strategy.

(vi). Benchmark comparison with international practice.

The strategies are presented graphically in Figure 7 in terms of percentage of bridge stock replacement cost. The range between Strategy B (0.27%) and Strategy D (1%) is shaded and represents the values between the minimum and optimum levels of investment which result in achieving full bridge network rehabilitation within the strategy time horizon and providing a minimum 85 year service life for all structures.

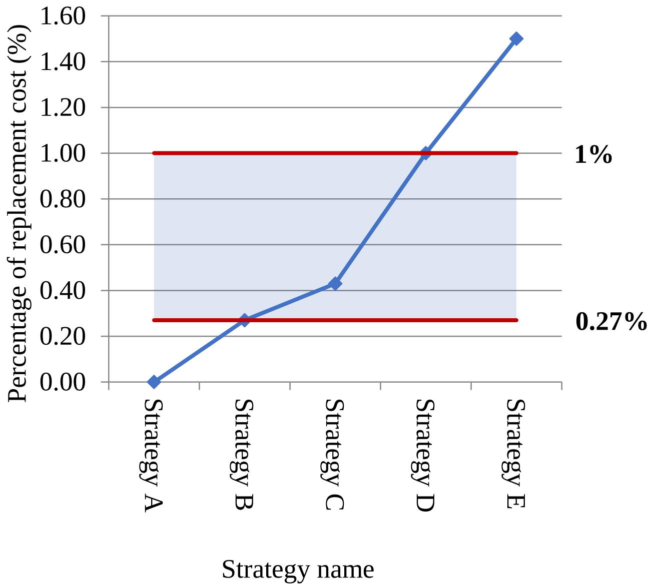


Figure 7. Optimum and minimum strategy range.

These findings confirm the applicability of the developed methodology:

- the range between the minimum and optimum investment levels is within the reported range of international practice (0.24% to 1.79%).
- the optimum investment level of 1% lies close to the calculated mean value of 0.92% for international practice.

## 3 CONCLUSIONS

This research has provided a methodology for the identification of a successful bridge rehabilitation strategy that takes into consideration the requirements for the prioritisation of rehabilitation projects, bridge deterioration and the limitations of funding resources. The key findings of the work are:

- The identification of a successful rehabilitation strategy requires consideration and evaluation of bridge structure deterioration, project prioritisation and strategy optimisation.
- An annual deterioration rate of 0.057 in bridge condition rating has been established and equates to a one point disimprovement in rating every 17.5 years.
- The research has confirmed that different motivations and judgements apply in the selection of rehabilitation projects for critical condition structures at or close to failure compared to non-critically damaged structures.
- For critical condition structures, the priority or sequence in which bridge rehabilitation projects were undertaken was found to be a function of the values of the overall structural condition and AADT variables, with the overall structural condition parameter being the most influential. Faced with a number of critical bridges, the calculated priority index confirms that the road authority adopted an approach based on firstly public safety and secondly on minimising disruption to heavily trafficked routes.
- For non-critical condition bridges, the priority index based on influencing factors from a survey of experts has been found to be a function of the values of the hydraulic vulnerability, the overall structural condition, the structural non-scour, AADT and road classification variables, with their influence ranked in that order.
- The minimum and optimum annual investments required in achieving full bridge network rehabilitation within the strategy time horizon and thus provide a minimum 85 year service life for all structures has been calculated as 0.27% and 1% respectively of the bridge stock replacement value. The current investment level of 0.43% lies within the minimum and optimum range.
- The application of the performance indicators of effectiveness and efficiency, taken from UK, New Zealand and French practice, and their evaluation by the concept of system performance has been shown to be a robust assessment process methodology that is confirmed with reference to international practice.

## ACKNOWLEDGMENTS

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## Appendix B

Typical Eirspan Principal Inspection Report

# Cork County Bridges Inventory Gathering and Principal Inspections

Structure Name:
**Dromcarra Bridge**
Structure ID:
**CC-R587-001.00**


**Client:**
Cork County Council,
County Hall,
Carrigrohane Road,
Cork.

**Engineer:**
Malachy Walsh and Partners.
Bessboro Road,
Mahon Technology Park,
Blackrock,
Cork.

| Document No | Revision | Prepared By | Checked By | Approved By | Status | Date |
|---|---|---|---|---|---|---|
| 14978-6531 | A | J Mc Carthy | M Murphy | P O'Donnell | Final Issue | May 2013 |
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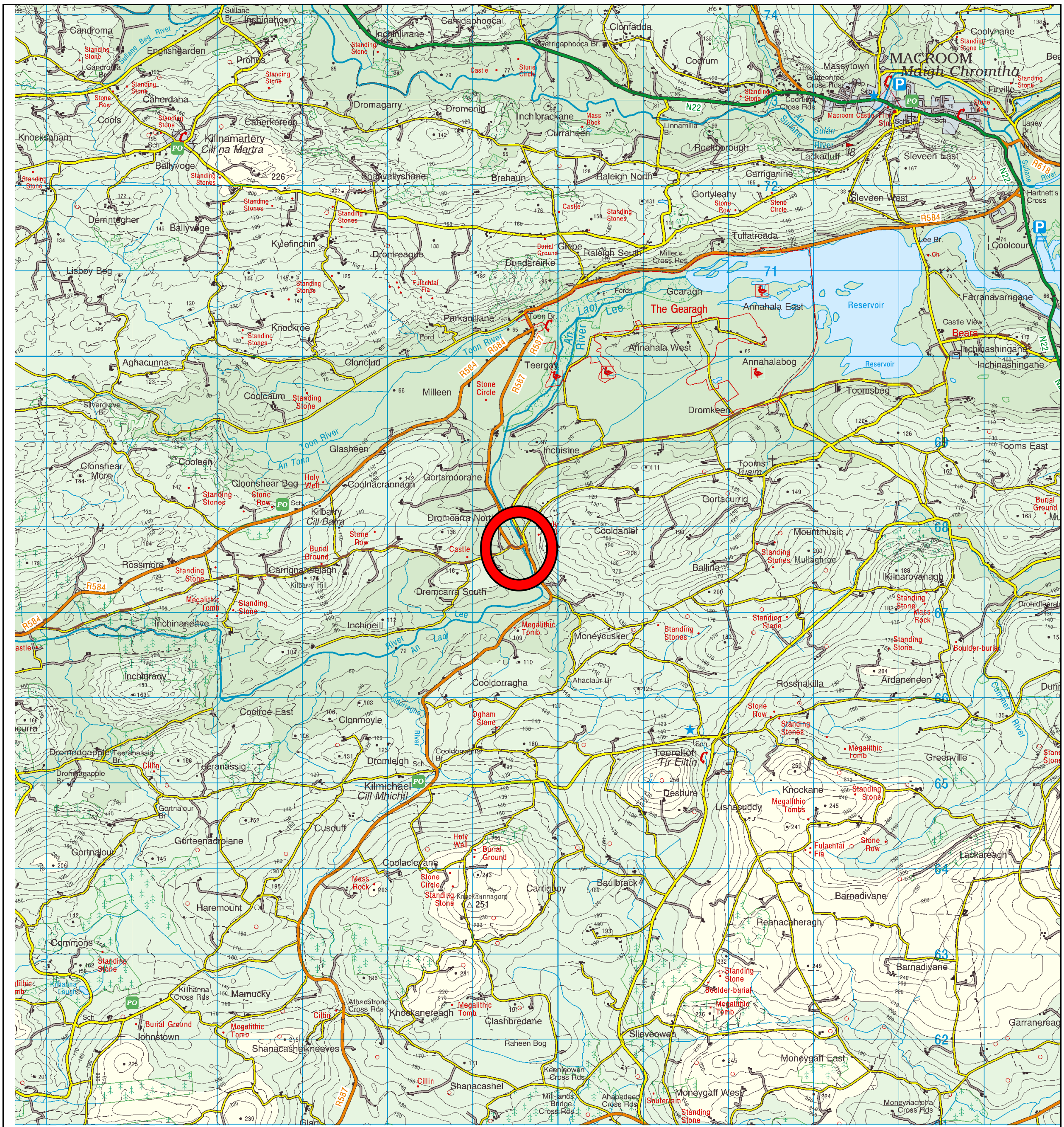


**Project:**

Cork County Bridges Inventory Gathering and Principal Inspections



**Figure:**

Figure 1

**Title:**

Location Map

**Structure Name:**

Dromcarra Bridge

Malachy Walsh and Partners
Consulting Engineers
Park House, Mahon Technology Park,
Bessboro Road, Blackrock, Cork
Tel: 021-4536400Fax: 021-4536450
http://www.mwp.ie

Maintaining Agent: 4 CC - Cork
Road............: Macroom - Dunmanway, County Cork
Side of road.....:
Plate and Dist...:

Region..........: 3 Munster
Struct. reg. no..: 1047

Year of construction..................:
Year of reconstruction................:

Primary passage Overbridge/Underbridge.: U
Dir. of chainage on primary road.......: N
Access equipment needed...............: 0 Nothing

Data collected : Date..................: 2013.05.22
Inspector Initials....: JMC
Checker Initials......: MM

Geographical position :
Latitude Y: 67763.100 Longitude X: 129562.100 m

Geometry : Number of spans.............: 4
Min span length..........(m): 5.44
Max span length..........(m): 5.56
Overall length...........(m): 25.84
Width out-to-out.........(m): 7.60
Width of median..........(m): 0.00
Width of footway left....(m): 0.20
Width of footway right...(m): 0.00
Width of carriageway.....(m): 5.29
Width kerb-to-kerb.......(m): 5.66
Width of approach....... (m): 5.62
Area...................(m2): 196.38

Minimum Parapet Height...(m): 0.90
Width of Soft Verge......(m): 0.29
Approach Skew 1........(deg): 45.00
Approach Skew 2........(deg): 30.00

Bridge curved..........(Y/N): N
Skew..................(deg): 0

Span Lengths:

| | | | | | |
|---|---|---|---|---|---|
| Span 1....(m): | 5.53 | Span 6....(m): | 0.00 | Span 11...(m): | 0.00 |
| Span 2....(m): | 5.56 | Span 7....(m): | 0.00 | Span 12...(m): | 0.00 |
| Span 3....(m): | 5.44 | Span 8....(m): | 0.00 | Span 13...(m): | 0.00 |
| Span 4....(m): | 5.53 | Span 9....(m): | 0.00 | Span 14...(m): | 0.00 |
| Span 5....(m): | 0.00 | Span 10...(m): | 0.00 | | |

Superstructure, principal type:
Standard design................(Y/N): Y
Design of cross section.............: 60 Masonry arch
Design of elevation.................: 50 Arch, one or more spans
Material of primary members..........: 60 Stone masonry

Superstructure, secondary type (if applicable):
Standard design................(Y/N): Y
Design of cross section.............: 10 Slab
Design of elevation.................: 10 Simple span, cons. cross sect.
Material of primary members..........: 20 In situ Reinforced Concrete

Masonry arch (if applicable):

| | |
|---|---|
| Span length.......................(m): | 5.53 |
| Rise of arch barrel at crown......(m): | 2.27 |
| Rise of arch barrel,quarter points(m): | 1.87 |
| Springing height above mudline....(m): | 2.00 |
| Thickness of arch barrel..........(m): | 0.58 |
| Average depth of fill.............(m): | 0.52 |
| Parapet thickness.................(m): | 0.32 |

| | Material: | Square cut/rubble (S/R): |
|---|---|---|
| Arch facing stones..: | 10 Limestone | R |
| Arch barrel sheeting: | 10 Limestone | R |
| Spandrel walls......: | 10 Limestone | R |

| | Average joint thickness: | Mortar strength Soft/Hard: |
|---|---|---|
| Arch facing stones..: | 30 More than 25mm | S |
| Arch barrel sheeting: | 30 More than 25mm | S |
| Spandrel walls......: | 30 More than 25mm | S |

Retaining wall (if applicable):

Overall length...................(m):
Height...........................(m):
Thickness at top.................(m):
Thickness at bottom..............(m):
Area outer surface..............(m2):
Type................................:
Material............................:
Foundation..........................:

```
Substructure:
  Abutment : Type......................:    11 Abutm. wall, indep. wing walls
             Material..................:    10 Masonry
             Foundation................:    10 Spread footing

  Pier.... : Type......................:    10 Solid wall
             Material..................:    10 Masonry
             Foundation................:    10 Spread footing
Details:
  Type of parapet......................:    60 Light steel railing
  Type of safety barrier...............:     0 No guard rail
  Type of wearing surface..............:    20 Bituminous surface dressing
  Type of expansion joint..............:    50 No joint device

  Type of fixed bearings on support....:    10 Construction joint
  Type of free bearings on support.....:    10 Construction joint
  Type of fixed bearings in girders....:    91 Not applicable
  Type of free bearings in girders.....:    91 Not applicable



Obstacle:
  Type of passage........:    31 River
  Passage id.............:
  Passage name...........:       River Lee
  Road side..............:
  Chainage...............:

Overpass passage:
  Design load............:
  Load distribution class:
  Technical standard used:             Unknown standard
  Bridge class normal....:
  Bridge class restricted:
  Max. axle load......(t):

Vertical clearance:
  Primary passage.....(m):   L:         LM:         RM:         R:
  Secondary passage...(m):   L:         LM:  4.27   RM:         R:

Owner....................:     4 Cork County Council
Maintaining Agent........:     4 Cork County Council
Inspection Consultant....:   115 Malachy Walsh/O'Connor Sutton Cronin
Designer.................:    92 Unknown

Technical documents......:
Technical installations..:     0 No technical installation

Remarks:
  Width of soft verge right = 0.45
  Secondary structure is 0.9m wide in situ concrete widening on both sides of
  the structure.
  Flood relief arch to south of structure: u/s concrete structure, 3.0m span, 1.
  5m vert clearance, concrete blockwork abutments, reinforced concrete slab.
  South abutment 6.76m, northern 5.57m long. Downstream of that is masonry
  structure skewed to u/s section, 3.64m span and 5.53m wide, springing to mud
```

Chronological overview :

| Date | Activity | 1 Br | 2 Ex | 3 Fo | 4 Pa | 5 Em | 6 Wi | 7 Ab | 8 Pi | 9 Be | 10 De | 11 Be | 12 Ri | 13 Ot | 14 St |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 2013.05.22 | Principal inspec | 1 | - | 1 | 2 | 1 | 2 | 2 | 2 | - | 3 | - | 2 | - | 3 |

Last principal inspection:

Date.................................: 2013.05.22
Team Leader Name.....................: Jerome Mc Carthy
Initials.............................: JMC
Weather..............................: Sunny
Temperature..................(deg. C): 11

Traffic: Annual Average Daily Traffic :
Percentage, light vehicles.. :
Percentage, heavy vehicles.. :

Year for next principal inspection... : 2016

Remark:

Defects to flood relief arch to south: repoint around crown of masonry arch 12m^2, Concrete patch repair to eroded blockwork in upstream section abutments.

| No | Component<br>Repair work<br>- Damage description<br>Type of damage | Con rtg | Mtn rtg | Spe Ins | Repair work TP | Qty | Year | Cost | Photos |
|---|---|---|---|---|---|---|---|---|---|
| 1 | Bridge surface<br>- Sweeping of verges required under routine maintenance.<br>Photo 1 - View over structure from south<br>Photo 2 - Surfacing on the structure | 1 | - | | | | | | 2 |
| 2 | Expansion joints | - | | | | | | | |
| 3 | Footways/median<br>- Rubbing strip adjacent to parapet plinth in good condition. Sweeping of surface required under routine maintenance.<br>Photo 1 - Portion of rubbing strip on upstream side of the bridge | 1 | - | | | | | | 1 |
| 4 | Parapets/Safety barrier | 2 | - | | | | | | 2 |
| | G:Cleaning and painting, light parapet | | | | G | 61 | 2016 | 12200 | |
| | - Parapet consists of 5 6.05m long sections of galvanised tubular steel. All require repainting. Surfaces to be cleaned under routine maintenance.<br>Photo 1 - upstream parapet<br>Photo 2 - downstream parapet<br>Material deterioration | | | | | | | | |
| 5 | Embankments/Revetments<br>- All embankments are in good condition.<br>Photo 1 - Right hand embankment on downstream side<br>Photo 2 - Right hand embankment on upstream side | 1 | + | | | | | | 2 |

| No | Component<br>Repair work<br>- Damage description<br>Type of damage | Con rtg | Mtn rtg | Spe Ins | Repair work TP | Qty | Year | Cost | Photos |
|---|---|---|---|---|---|---|---|---|---|
| 6 | Wing/Spandrel/Retaining Walls | 2 | - | | | | | | 3 |
| | D:Masonry repointing | | | | D | 8 | 2015 | 1000 | |
| | Z:Other repair work | | | | Z | 3 | 2015 | 11700 | |
| | - Vegetation clearance is required. Right hand wing wall on upstream side separating from abutment and the masonry section under the concrete is bulging. Install soil nails and repoint. Left hand wing wall on the downstream side has been scoured adjacent to the abutment.<br>Photo 1 - Left hand wing wall on the downstream side<br>Photo 2 - Masonry at base of right hand wing wall upstream<br>Photo 3 - Right hand wing wall upstream of structure | | | | | | | | |
| | Tilt / settlement | | | | | | | | |
| 7 | Abutments | 2 | - | | | | | | 2 |
| | A:Concrete repair (without reinforceme | | | | A | 2 | 2016 | 1820 | |
| | - Right hand abutment is ok, the scour protection should be replaced. Left hand abutment is ok.<br>Vegetation removal required under routine maintenance.<br>Photo 1 - Right hand abutment and downstream wing wall<br>Photo 2 - Left hand wing wall | | | | | | | | |
| | Erosion / scour | | | | | | | | |
| 8 | Piers | 2 | - | | | | | | 4 |
| | D:Masonry repointing | | | | D | 48 | 2016 | 8710 | |
| | A:Concrete repair (without reinforceme | | | | A | 12 | 2016 | 10920 | |
| | - Pier 1 (south) repoint lower 1m and replace scour protection. Masonry repair to upstream cutwater. Pier 2 (mid) repoint lower 1m and repoint upstream cutwater. Pier 3 (north) replace scour protection.<br>Photo 1 - Upstream end of pier 1<br>Photo 2 - Right hand side of pier 2<br>Photo 3 - Open jointing on right hand side of pier 2<br>Photo 4 - Left hand side of pier 3 | | | | | | | | |
| | Erosion / scour | | | | | | | | |
| 9 | Bearings | - | | | | | | | |

| No Component<br>Repair work<br>- Damage description<br>Type of damage | Con rtg | Mtn rtg | Spe Ins | Repair work TP | Qty | Year | Cost | Photos |
|---|---|---|---|---|---|---|---|---|
| 10 Deck/slab/arch barrel | 3 | + | | | | | | 4 |
| D:Masonry repointing | | | | D | 60 | 2014 | 11100 | |
| - Spans 2 to 4 have concrete arches and are in a good condition. Span 1 (south) is masonry in need of repointing. Circumferential crack 0.5m from upstream and downstream ends. Arch in flood relief span to be repointed.<br>Photo 1 - Span 3 arch and concrete slab from upstream end.<br>Photo 2 - Span 1 arch and concrete slab from upstream end.<br>Photo 3 - Intrados of arch in span 1<br>Photo 4 - Intrados of arch in flood relief span | | | | | | | | |
| Material deterioration | | | | | | | | |
| 11 Beams/girders/transverse beams | - | | | | | | | |
| 12 Riverbed | 2 | - | | | | | | 1 |
| Z:Other repair work | | | | Z | 9 | 2015 | 4550 | |
| - Trees and debris caught at upstream ends of piers to be removed under routine maintenance. Uneven masonry bed lining to majority of structure. Section damaged at downstream end of span 4. Masonry repair to riverbed to be carried out.<br>Photo 1 - section of masonry loss to bed lining in span 4 | | | | | | | | |
| Erosion / scour | | | | | | | | |
| 13 Other elements | - | | | | | | | |
| 14 Structure in general | 3 | - | | | | | | 2 |
| - Condition of deck determines overall rating<br>Photo 1 - Downstream elevation<br>Photo 2 - Downstream elevation of flood relief span | | | | | | | | |
| Total cost | | | | | | | 62000 | |


Component..........: 1 Bridge surface

Condition/Mainten..: 1 / -

Damage/Remarks.....: Sweeping of verges required under routine maintenance.
Photo 1 - View over structure from south
Photo 2 - Surfacing on the structure


Component..........: 1 Bridge surface

Condition/Mainten..: 1 / -

Damage/Remarks.....: Sweeping of verges required under routine maintenance.
Photo 1 - View over structure from south
Photo 2 - Surfacing on the structure


Component..........: 3 Footways/median

Condition/Mainten..: 1 / -

Damage/Remarks.....: Rubbing strip adjacent to parapet plinth in good condition. Sweeping of surface required under routine maintenance.
Photo 1 - Portion of rubbing strip on upstream side of the bridge


Component..........: 4 Parapets/Safety barrier

Condition/Mainten..: 2 / -

Damage/Remarks.....: Parapet consists of 5 6.05m long sections of galvanised tubular steel. All require repainting. Surfaces to be cleaned under routine maintenance.
Photo 1 - upstream parapet
Photo 2 - downstream parapet

Damage type........: Material deterioration

Repair works.......: G Cleaning and painting, light parapet


Component..........: 4 Parapets/Safety barrier

Condition/Mainten..: 2 / -

Damage/Remarks.....: Parapet consists of 5 6.05m long sections of galvanised tubular steel. All require repainting. Surfaces to be cleaned under routine maintenance.
Photo 1 - upstream parapet
Photo 2 - downstream parapet

Damage type........: Material deterioration

Repair works.......: G Cleaning and painting, light parapet


Component..........: 5 Embankments/Revetments

Condition/Mainten..: 1 / +

Damage/Remarks.....: All embankments are in good condition.
Photo 1 - Right hand embankment on downstream side
Photo 2 - Right hand embankment on upstream side


Component..........: 5 Embankments/Revetments

Condition/Mainten..: 1 / +

Damage/Remarks.....: All embankments are in good condition.
Photo 1 - Right hand embankment on downstream side
Photo 2 - Right hand embankment on upstream side


Component..........: 6 Wing/Spandrel/Retaining Walls

Condition/Mainten..: 2 / -

Damage/Remarks.....: Vegetation clearance is required. Right hand wing wall on upstream side separating from abutment and the masonry section under the concrete is bulging. Install soil nails and repoint. Left hand wing wall on the downstream side has been scoured adjacent to the abutment.
Photo 1 - Left hand wing wall on the downstream side

Damage type........: Tilt / settlement

Repair works.......: D Masonry repointing
Z Other repair work


Component..........: 6 Wing/Spandrel/Retaining Walls

Condition/Mainten..: 2 / -

Damage/Remarks.....: Vegetation clearance is required. Right hand wing wall on upstream side separating from abutment and the masonry section under the concrete is bulging. Install soil nails and repoint. Left hand wing wall on the downstream side has been scoured adjacent to the abutment.
Photo 1 - Left hand wing wall on the downstream side

Damage type........: Tilt / settlement

Repair works.......: D Masonry repointing
Z Other repair work


Component..........: 6 Wing/Spandrel/Retaining Walls

Condition/Mainten..: 2 / -

Damage/Remarks.....: Vegetation clearance is required. Right hand wing wall on upstream side separating from abutment and the masonry section under the concrete is bulging. Install soil nails and repoint. Left hand wing wall on the downstream side has been scoured adjacent to the abutment.
Photo 1 - Left hand wing wall on the downstream side

Damage type........: Tilt / settlement

Repair works.......: D Masonry repointing
Z Other repair work


Component..........: 7 Abutments

Condition/Mainten..: 2 / -

Damage/Remarks.....: Right hand abutment is ok, the scour protection should be replaced. Left hand abutment is ok. Vegetation removal required under routine maintenance.
Photo 1 - Right hand abutment and downstream wing wall
Photo 2 - Left hand wing wall

Damage type........: Erosion / scour

Repair works.......: A Concrete repair (without reinforcement)


Component..........: 7 Abutments

Condition/Mainten..: 2 / -

Damage/Remarks.....: Right hand abutment is ok, the scour protection should be replaced. Left hand abutment is ok. Vegetation removal required under routine maintenance.
Photo 1 - Right hand abutment and downstream wing wall
Photo 2 - Left hand wing wall

Damage type........: Erosion / scour

Repair works.......: A Concrete repair (without reinforcement)


Component..........: 8 Piers

Condition/Mainten..: 2 / -

Damage/Remarks.....: Pier 1 (south) repoint lower 1m and replace scour protection. Masonry repair to upstream cutwater. Pier 2 (mid) repoint lower 1m and repoint upstream cutwater. Pier 3 (north) replace scour protection.
Photo 1 - Upstream end of pier 1
Photo 2 - Right hand side of pier 2
Photo 3 - Open jointing on right hand side of pier 2

Damage type........: Erosion / scour

Repair works.......: D Masonry repointing
A Concrete repair (without reinforcement)


Component..........: 8 Piers

Condition/Mainten..: 2 / -

Damage/Remarks.....: Pier 1 (south) repoint lower 1m and replace scour protection. Masonry repair to upstream cutwater. Pier 2 (mid) repoint lower 1m and repoint upstream cutwater. Pier 3 (north) replace scour protection.
Photo 1 - Upstream end of pier 1
Photo 2 - Right hand side of pier 2
Photo 3 - Open jointing on right hand side of pier 2

Damage type........: Erosion / scour

Repair works.......: D Masonry repointing
A Concrete repair (without reinforcement)


Component..........: 8 Piers

Condition/Mainten..: 2 / -

Damage/Remarks.....: Pier 1 (south) repoint lower 1m and replace scour protection. Masonry repair to upstream cutwater. Pier 2 (mid) repoint lower 1m and repoint upstream cutwater. Pier 3 (north) replace scour protection.
Photo 1 - Upstream end of pier 1
Photo 2 - Right hand side of pier 2
Photo 3 - Open jointing on right hand side of pier 2

Damage type........: Erosion / scour

Repair works.......: D Masonry repointing
A Concrete repair (without reinforcement)


Component..........: 8 Piers

Condition/Mainten..: 2 / -

Damage/Remarks.....: Pier 1 (south) repoint lower 1m and replace scour protection. Masonry repair to upstream cutwater. Pier 2 (mid) repoint lower 1m and repoint upstream cutwater. Pier 3 (north) replace scour protection.
Photo 1 - Upstream end of pier 1
Photo 2 - Right hand side of pier 2
Photo 3 - Open jointing on right hand side of pier 2

Damage type........: Erosion / scour

Repair works.......: D Masonry repointing
A Concrete repair (without reinforcement)


Component..........: 10 Deck/slab/arch barrel

Condition/Mainten..: 3 / +

Damage/Remarks.....: Spans 2 to 4 have concrete arches and are in a good condition. Span 1 (south) is masonry in need of repointing. Circumferential crack 0.5m from upstream and downstream ends. Arch in flood relief span to be repointed.
Photo 1 - Span 3 arch and concrete slab from upstream end.

Damage type........: Material deterioration

Repair works.......: D Masonry repointing


Component..........: 10 Deck/slab/arch barrel

Condition/Mainten..: 3 / +

Damage/Remarks.....: Spans 2 to 4 have concrete arches and are in a good condition. Span 1 (south) is masonry in need of repointing. Circumferential crack 0.5m from upstream and downstream ends. Arch in flood relief span to be repointed.
Photo 1 - Span 3 arch and concrete slab from upstream end.

Damage type........: Material deterioration

Repair works.......: D Masonry repointing


Component..........: 10 Deck/slab/arch barrel

Condition/Mainten..: 3 / +

Damage/Remarks.....: Spans 2 to 4 have concrete arches and are in a good condition. Span 1 (south) is masonry in need of repointing. Circumferential crack 0.5m from upstream and downstream ends. Arch in flood relief span to be repointed.
Photo 1 - Span 3 arch and concrete slab from upstream end.

Damage type........: Material deterioration

Repair works.......: D Masonry repointing


Component..........: 10 Deck/slab/arch barrel

Condition/Mainten..: 3 / +

Damage/Remarks.....: Spans 2 to 4 have concrete arches and are in a good condition. Span 1 (south) is masonry in need of repointing. Circumferential crack 0.5m from upstream and downstream ends. Arch in flood relief span to be repointed.
Photo 1 - Span 3 arch and concrete slab from upstream end.

Damage type........: Material deterioration

Repair works.......: D Masonry repointing


Component..........: 12 Riverbed

Condition/Mainten..: 2 / -

Damage/Remarks.....: Trees and debris caught at upstream ends of piers to be removed under routine maintenance. Uneven masonry bed lining to majority of structure. Section damaged at downstream end of span 4. Masonry repair to riverbed to be carried out. Photo 1 - section of masonry loss to bed lining in span 4

Damage type........: Erosion / scour

Repair works.......: Z Other repair work


Component..........: 14 Structure in general

Condition/Mainten..: 3 / -

Damage/Remarks.....: Condition of deck determines overall rating
Photo 1 - Downstream elevation
Photo 2 - Downstream elevation of flood relief span


Component..........: 14 Structure in general

Condition/Mainten..: 3 / -

Damage/Remarks.....: Condition of deck determines overall rating
Photo 1 - Downstream elevation
Photo 2 - Downstream elevation of flood relief span

## Appendix C

List of bridges in the study dataset

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|---|---|
| CC-1123-001.00 | Tullig Bridge | CC-L1010-002.00 | Meendurragha Bridge | CC-L1108-001.00 | Doon Bridge |
| CC-5210-002.00 | Fortgrady East Bridge | CC-L10101-001.00 | Glentanefinnane East Bridge | CC-L1108-002.00 | Athnaloingebaine Bridge |
| CC-L1000-001.00 | Rockchapel Bridge | CC-L1013-001.00 | Inchantotane Bridge | CC-L1114-001.00 | Cullen Bridge |
| CC-L1001-001.00 | Meennarahee Bridge | CC-L1017--001.00 | Priory Bridge | CC-L1116-001.00 | Wallis's Bridge |
| CC-L10012-001.00 | Knockatooan East Bridge | CC-L1018-001.00 | Anne's Bridge | CC-L1117-001.00 | Colthurst Bridge |
| CC-L1002-002.00 | Conny's Bridge | CC-L1018-002.00 | Long Bridge | CC-L1118-001.00 | Bride's Bridge |
| CC-L1002-003.00 | Barry's Bridge | CC-L1020-001.00 | Grillough Bridge | CC-L1118-002.00 | Fortgrady Bridge |
| CC-L1003-001.00 | Nelly's Bridge | CC-L1021-001.00 | Allen's Bridge North | CC-L1118-003.00 | Carraraigue Bridge |
| CC-L1004-001.00 | Cloghvoula Bridge | CC-L1021-002.00 | Allens Bridge South | CC-L1119-001.00 | Lyons Bridge |
| CC-L1004-002.00 | Cloghvoula South Bridge | CC-L1021-003.00 | Derrygallun Bridge | CC-L1119-002.00 | Muinygoreen Bridge |
| CC-L1004-003.00 | Cappa Bridge | CC-L1025-001.00 | Daly's Mill | CC-L1119-003.00 | Kilcorney Bridge |
| CC-L1004-004.00 | Glenlahan Bridge | CC-L1026-001.00 | Coolacoosane Bridge | CC-L1119-004.00 | Lackloun Bridge |
| CC-L1004-005.00 | Sheahan's Bridge | CC-L1033-001.00 | Brogeen Bridge | CC-L1120-001.00 | Rathcoole Bridge |
| CC-L1005-001.00 | Rowls South Bridge | CC-L1035-001.00 | Renagashel Bridge | CC-L1121-001.00 | Roskeen Bridge 1 |
| CC-L1007-001.00 | Twomey's Bridge | CC-L1035-002.00 | Kilnahulla Bridge | CC-L1121-002.00 | Roskeen Bridge 2 |
| CC-L1007-002.00 | Meenkearagh North Bridge | CC-L1041-001.00 | Ketragh Bridge | CC-L1122-002.00 | Gortmore North Bridge |
| CC-L1007-003.00 | Meenkearagh South Bridge | CC-L1042-001.00 | Bannagh Br | CC-L1122-003.00 | Banteer Bridge |
| CC-L10072-001.00 | Knockduff Upper North Bridge | CC-L1044-001.00 | Assolas Bridge | CC-L1123-002.00 | Owenbaun Bridge |
| CC-L10074-001.00 | Knockduff Lower Bridge | CC-L1044-002.00 | Ketragh Bridge | CC-L1123-003.00 | Mushera Bridge |
| CC-L1008-001.00 | Ballynaguilla Bridge | CC-L1051-001.00 | Garraunawarrig Lower Bridge | CC-L11241-001.00 | Donoure Bridge |
| CC-L1009-001.00 | Bridge Street Bridge Clonakilty | CC-L1102-001.00 | Dernagree Bridge | CC-L1125-001.00 | Monaveel Bridge |
| CC-L1010-001.00 | Glentanefinnane West Bridge | CC-L1104-001.00 | Lisheen Bridge | CC-L1126-001.00 | Lacka Bridge |
| CC-L1130-001.00 | Hollymount Bridge | CC-L12131-001.00 | Boola Bridge | CC-L1303-002.00 | Kyle Bridge |
| CC-L1130-002.00 | Mountleader Bridge | CC-L1214-001.00 | Lyre Bridge | CC-L1305-001.00 | John's Bridge |
| CC-L1130-003.00 | Ahaphooca Bridge | CC-L1214-002.00 | Tobergal Bridge | CC-L1312-001.00 | New Line Bridge |
| CC-L1130-004.00 | Gortavehy Bridge | CC-L1214-003.00 | Glashaboy Bridge | CC-L1319-001.00 | Spa Bridge |
| CC-L1130-005.00 | Tourboney Bridge | CC-L1215-001.00 | Ballynamona Bridge | CC-L1319-002.00 | Dreenagh East Bridge |
| CC-L1200-001.00 | Lodge Bridge | CC-L1216-001.00 | Hackett's Bridge | CC-L1320-001.00 | Imphrick Bridge |
| CC-L1200-002.00 | Copsetown Bridge | CC-L1217-001.00 | Greenhill West Bridge | CC-L1320-002.00 | Ballindillanig Bridge |
| CC-L1203-001.00 | Glenreagh Bridge | CC-L1217-002.00 | Burnfort Bridge | CC-L1320-003.00 | Liscarroll Bridge |
| CC-L1203-003.00 | Blossomfort Bridge | CC-L1217-003.00 | Tooreen North Lower Bridge | CC-L1321-001.00 | Ballynamuck Bridge |
| CC-L1205-001.00 | Lisleagh Bridge | CC-L1219-001.00 | Brown Bridge | CC-L1322-001.00 | Egmont Bridge |
| CC-L12053-001.00 | Baltydaniel West Bridge | CC-L1219-002.00 | Knuttery Bridge | CC-L1322-002.00 | Ahatnaha Bridge |
| CC-L12054-001.00 | Mountnorth Bridge | CC-L1222-001.00 | Ballynageehy Bridge | CC-L1326-001.00 | Rossagh East Bridge |
| CC-L1206-001.00 | Ballynafeaha Bridge | CC-L1223-001.00 | Ballygarret Bridge | CC-L1328-001.00 | Ballyhoura Bridge 1 |
| CC-L1206-002.00 | Kilgobban Bridge | CC-L1223-003.00 | Ahaunaboy Bridge | CC-L1328-002.00 | Ballyhoura Bridge 2 |
| CC-L1207-001.00 | Ironmine Bridge | CC-L12233-001.00 | Dromrahan Bridge | CC-L1331-001.00 | Carker Bridge |
| CC-L1209-001.00 | Lombardstown Bridge | CC-L1224-001.00 | Ross Bridge | CC-L1400-001.00 | Ballyguyroe Bridge |
| CC-L1210-001.00 | Lombardstown South Bridge | CC-L1225-001.00 | Kilcummer Bridge | CC-L1400-002.00 | Drohidnagour Bridge |
| CC-L1210-002.00 | Brittas Bridge | CC-L1225-002.00 | Killavullen Bridge | CC-L1401-001.00 | Meadstown Bridge |

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|---|---|
| CC-L1210-003.00 | Knockansweeny Bridge | CC-L1226-001.00 | Monanimy Lower Bridge | CC-L1402-001.00 | Ballywalter Bridge |
| CC-L1211-001.00 | Gortroe South Bridge | CC-L1226-002.00 | Carleton Bridge | CC-L1405-001.00 | Marshalstown Bridge |
| CC-L1211-002.00 | Gortmolire Bridge | CC-L12272-001.00 | Monanimy Upper Bridge | CC-L1406-001.00 | Carrigane Bridge |
| CC-L1211-003.00 | Knockavaddra Bridge | CC-L1232-001.00 | Lackanalooha Bridge | CC-L1406-002.00 | Ballygiblin Church Culvert |
| CC-L1407-001.00 | Killee Bridge | CC-L1508-001.00 | Millquarter bridge | CC-L20115-001.00 | Alcocks Bridge |
| CC-L1411-001.00 | Ballykenly Bridge | CC-L1511-001.00 | Glenabo Bridge | CC-L2014-001.00 | Gurteen Bridge(b) |
| CC-L1415-001.00 | Glanworth Bridge | CC-L1516-001.00 | Conna Bridge | CC-L2014-002.00 | Cappaknockane Bridge |
| CC-L1416-001.00 | Glencorra Bridge | CC-L1516-002.00 | Coole Bridge | CC-L2014-003.00 | Kilcolman Bridge |
| CC-L1418-001.00 | Ballynamona Bridge | CC-L1519-001.00 | Bride Bridge | CC-L2014-004.00 | Roseville Bridge |
| CC-L1418-002.00 | Killikane Bridge | CC-L1525-001.00 | Bluebell Bridge | CC-L2014-005.00 | Ballinannaghree Bridge |
| CC-L1418-003.00 | Pollardstown Bridge | CC-L15302-001.00 | Shankill East Bridge | CC-L2015-001.00 | Farrannasheshery Bridge |
| CC-L1419-001.00 | Mountain Barrack Bridge | CC-L1532-001.00 | Bridepark Bridge | CC-L2019-001.00 | Baxter's Bridge |
| CC-L1419-002.00 | Glansheskin Bridge | CC-L1540-001.00 | Meenane Bridge | CC-L2033-001.00 | Gurteen Bridge |
| CC-L1420-001.00 | Curraghavoe Bridge | CC-L2000-001.00 | Ballymichael Bridge | CC-L2045-001.00 | Corravreeda East Bridge |
| CC-L1420-002.00 | Glenduff Bridge | CC-L2003-001.00 | Currabeha Bridge | CC-L2047-001.00 | Ballynough Bridge |
| CC-L1421-001.00 | Araglin Bridge | CC-L2004-001.00 | Horn Hill Bridge | CC-L2051-001.00 | Murragh Bridge |
| CC-L1421-002.00 | Glenfinish Bridge | CC-L2005-001.00 | Kilnacranagh Bridge | CC-L2063-001.00 | Oldchapel Bridge |
| CC-L1421-003.00 | Elizabeth's Bridge | CC-L2006-001.00 | Glannarouge X Roads Bridge | CC-L2202-001.00 | Rooves Moore North Bridge |
| CC-L1421-004.00 | Crinnaghtane Bridge | CC-L2006-002.00 | Bealanafohill Bridge | CC-L2203-001.00 | Cloghduff Bridge |
| CC-L1421-005.00 | Gortnaskehy Bridge | CC-L20071-001.00 | Belrose Upper South Bridge | CC-L2205-001.00 | Ryecourt Bridge |
| CC-L1422-001.00 | Douglas Bridge | CC-L20071-002.00 | Belrose Upper North Bridge | CC-L2206-001.00 | Coolmucky Bridge |
| CC-L1423-001.00 | Coolmoohan Bridge | CC-L20101-001.00 | Farranlugh Bridge | CC-L2216-001.00 | Killumney Bridge |
| CC-L1423-002.00 | Bakers Bridge | CC-L2011-001.00 | Ballaghcloghane Bridge | CC-L2216-002.00 | Ballygroman Lower Bridge |
| CC-L1445-001.00 | Ballynahow Bridge | CC-L2011-002.00 | Mallowgaton Bridge | CC-L2216-003.00 | Stickstown Bridge |
| CC-L1502-001.00 | Ballymacphillip North Bridge | CC-L20111-001.00 | Glannarouge Bridge | CC-L2218-001.00 | Ballyhandle South Bridge |
| CC-L1502-002.00 | Ballymacphilip South Bridge | CC-L20111-002.00 | Ahalarick Bridge | CC-L2219-001.00 | Greenfields Bridge |
| CC-L2220-001.00 | Maglin West Bridge | CC-L2452-001.00 | Liberty Bridge | CC-L2760-001.00 | Tulligmore Bridge |
| CC-L2220-002.00 | Maglin North Bridge | CC-L2452-002.00 | Spur Hill Railway Bridge | CC-L2760-002.00 | Callas Bridge |
| CC-L2222-001.00 | Curraheen Bridge | CC-L2455-001.00 | Corcoran's Bridge | CC-L2761-001.00 | Dripsey Castle Bridge |
| CC-L2222-001.01 | Curraheen Bridge | CC-L2455-002.00 | Lehenagh Beg Railway Bridge | CC-L2762-002.00 | Dromgownagh East Bridge |
| CC-L2222-002.00 | Maglin South Bridge | CC-L2458-001.00 | Ballycurreen Bridge | CC-L2762-003.00 | Ballyanly Bridge |
| CC-L2223-001.00 | Ballynora Bridge | CC-L2466-001.00 | Church Road Bridge | CC-L2764-001.00 | Rubys Bridge |
| CC-L2224-001.00 | Ballymah Bridge | CC-L2467-001.00 | Dry Bridge | CC-L2764-002.00 | Foxes Bridge |
| CC-L2225-001.00 | Oldabbey East Bridge | CC-L2490-001.00 | Ballyhemiken Bridge | CC-L27643-001.00 | Gort Bridge |
| CC-L2225-002.00 | Oldabbey Bridge | CC-L2493-001.00 | Healy's Bridge | CC-L2767-001.00 | Maulrane Bridge |
| CC-L2227-001.00 | Rearour Bridge | CC-L2750-001.00 | Dripsey Bridge Lower | CC-L2773-001.00 | Game Bridge |
| CC-L2230-001.00 | Abbey Bridge | CC-L2751-001.00 | Miskellas Bridge | CC-L2773-002.00 | Putlands Bridge |
| CC-L2234-002.00 | Killeen Bridge | CC-L2752-002.00 | Kilclogh South Bridge | CC-L2777-001.00 | Healys Bridge |
| CC-L2235-001.00 | Ballinacurra Bridge | CC-L2753-001.00 | St. Olan's Well Bridge | CC-L2780-001.00 | Banafinny Bridge |
| CC-L2236-001.00 | Dardan Bridge | CC-L2758-001.00 | Dripsey Upper Bridge | CC-L2781-001.00 | Bannow Bridge |

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|---|---|
| CC-L2782-001.00 | Kilnap Bridge | CC-L3213-001.00 | Ballythomas Bridge | CC-L3804-002.00 | Auvane Bridge |
| CC-L2782-002.00 | Glancam Bridge | CC-L3227-001.00 | White Castle Bridge | CC-L3805-001.00 | Ballymacoda Bridge |
| CC-L2782-003.00 | Monard East Bridge | CC-L34002-001.00 | Mills Bridge | CC-L3807-001.00 | Barngeehy Bridge |
| CC-L2785-001.00 | Monard West Bridge | CC-L3401-001.00 | Beal a Fionshn Bridge | CC-L3807-002.00 | Ballymacask Bridge |
| CC-L27881-001.00 | Horgans Bridge | CC-L3402-001.00 | Con Lynch's Bridge | CC-L3807-003.00 | Brooklodge Bridge |
| CC-L2796-001.00 | Wises Bridge | CC-L3403-001.00 | Derrineanig Bridge | CC-L3808-001.00 | Clasheel Bridge |
| CC-L2797-001.00 | Killard Bridge | CC-L3404-001.00 | Inchigeela Bridge | CC-L3808-002.00 | Muckridge Bridge |
| CC-L2952-001.00 | Poulagloger Bridge | CC-L3404-002.00 | Ballymakeery Bridge | CC-L3808-003.00 | Copperally Bridge |
| CC-L2954-001.00 | Carrignavar Bridge | CC-L3405-001.00 | Reinaniree Bridge | CC-L3809-001.00 | Mogeely Bridge |
| CC-L2956-001.00 | Ballyvorisheen Bridge | CC-L3409-001.00 | Clondrohid Bridge | CC-L3809-002.00 | Aghanasonnach Bridge |
| CC-L2956-002.00 | Glashanbrack Bridge | CC-L3409-002.00 | Ullanes Bridge | CC-L3811-001.00 | Fanisk South Bridge |
| CC-L2956-003.00 | Coom East Bridge | CC-L3413-001.00 | Raleigh Linnamilla Bridge | CC-L3811-002.00 | Finisk Old Bridge |
| CC-L2956-004.00 | Doonpeter Bridge | CC-L3415-001.00 | Codrum Bridge | CC-L3811-003.00 | Finisk New Bridge |
| CC-L2956-005.00 | Foleys Bridge | CC-L3417-001.00 | Coddeleenbaoun Bridge | CC-L38194-001.00 | Ballyalley Bridge |
| CC-L2958-001.00 | Dunbullogue Bridge | CC-L3418-001.00 | Carrigulla Bridge | CC-L4002-001.00 | Ballynavar Bridge |
| CC-L2958-002.00 | Anname Bridge | CC-L3418-002.00 | Capaleen Bßn Bridge | CC-L40073-001.00 | Creaghmore Bridge North |
| CC-L2958-003.00 | Graigue Bridge | CC-L3418-003.00 | Awboy Bridge | CC-L40073-002.00 | Creaghmore Bridge South |
| CC-L2958-004.00 | Glenville Bridge | CC-L3418-004.00 | Coolaniddane Bridge | CC-L4008-001.00 | Milltown Bridge |
| CC-L29585-001.00 | Lyre South Bridge | CC-L3419-001.00 | Knocknagapaul Bridge | CC-L4008-002.00 | Green Field Bridge |
| CC-L2961-001.00 | Tailors Bridge | CC-L3419-002.00 | Knocknagappul Bridge 2 | CC-L4015-001.00 | Darrary Bridge |
| CC-L2962-001.00 | Kilcully Bridge | CC-L3424-001.00 | Laney Bridge | CC-L4016-001.00 | Darrara Church Bridge |
| CC-L2963-001.00 | Glennmought Bridge | CC-L3428-001.00 | Athsollis Bridge | CC-L4020-001.00 | Ballinglanna Bridge |
| CC-L2964-001.00 | Kilquane Bridge | CC-L3601-001.00 | Monaleen Bridge | CC-L4026-001.00 | Inchy Bridge |
| CC-L2964-002.00 | Aghalig Bridge | CC-L3601-002.00 | Walshtown Bridge | CC-L4028-001.00 | Skeaf bridge |
| CC-L2964-003.00 | Rathfilode Bridge | CC-L3604-001.00 | Coolgarah Bridge | CC-L40301-001.00 | Monteen Bridge |
| CC-L29642-001.00 | Transtown South Bridge | CC-L3608-001.00 | Knockaheen | CC-L4032-001.00 | Garranecore Bridge |
| CC-L29643-001.00 | Coolguerisk Bridge | CC-L3608-002.00 | Curragh Bridge | CC-L40342-001.00 | Ahamilla Bridge |
| CC-L2966-001.00 | Drogendeneick Bridge | CC-L3609-001.00 | Corbally South Bridge | CC-L4040-001.00 | Bridge St Bridge |
| CC-L2966-003.00 | Riverstown Lower Bridge | CC-L3610-001.00 | Pine Cross Bridge | CC-L4206-001.00 | Rathmore Bridge |
| CC-L2972-001.00 | Ballingohig Bridge | CC-L3610-002.00 | Gortacrue Bridge | CC-L4211-001.00 | Lahertidaly Bridge |
| CC-L2998-001.00 | Riverstown Bridge | CC-L3611-001.00 | Lackenbehy Bridge | CC-L4212-001.00 | Ballyhilty Bridge |
| CC-L3002-001.00 | Ardnabricka Bridge | CC-L3614-001.00 | Ballyspillane West Bridge | CC-L4213-001.00 | Maulbrack Bridge |
| CC-L3010-001.00 | Glanmire Bridge | CC-L3638-001.00 | Shanahee Bridge | CC-L4214-001.00 | Lissalohrig Bridge |
| CC-L3203-001.00 | Ballinhassig Bridge | CC-L3644-001.00 | Inch Bridge | CC-L4215-001.00 | Carraig Bridge |
| CC-L3203-002.00 | Brown's Mills North Bridge | CC-L3800-001.00 | Dungourney Bridge | CC-L4219-001.00 | Downeen Bridge |
| CC-L3204-001.00 | Cloghane North Bridge | CC-L3800-002.00 | Sheepwalk Bridge | CC-L4220-001.00 | Currabeg Bridge |
| CC-L3204-002.00 | Cloghane South Bridge | CC-L38002-001.00 | Ballyre North Bridge | CC-L4221-001.00 | Rineen Bridge |
| CC-L32041-001.00 | Cloghane Bridge | CC-L3802-001.00 | Ballyknock Bridge | CC-L4225-001.00 | Poulgorm Bridge |
| CC-L3210-001.00 | Minane Bridge | CC-L3803-001.00 | Inch Bridge | CC-L4225-001.01 | Poulgorm Bridge |
| CC-L3210-002.00 | Tracton Bridge | CC-L3804-001.00 | Dangan Bridge | CC-L4230-001.00 | Lissane Lower Bridge |

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|---|---|
| CC-L4231-001.00 | Minanes Bridge | CC-L4631-001.00 | Ballineen Bridge | CC-L4934-001.00 | Dereenataggart East |
| CC-L4232-001.00 | Derryclough Lower Bridge | CC-L4631-002.00 | Coolnaconarty Bridge | CC-L4935-001.00 | Felane West Bridge |
| CC-L4235-001.00 | Corran North Bridge | CC-L4632-001.00 | Aghadoghtura Bridge | CC-L49352-001.00 | Shanacoumha Bridge |
| CC-L4235-002.00 | Corran Bridge | CC-L4635-001.00 | Oakmount Bridge | CC-L5002-001.00 | Glencarney Bridge |
| CC-L4235-003.00 | Reavouler Bridge | CC-L4637-001.00 | Kippagh Bridge | CC-L5003-001.00 | Lyraneag Bridge |
| CC-L4238-001.00 | Milleenahillian Bridge | CC-L4638-001.00 | Inchinattin Bridge | CC-L5007-001.00 | Tooreenfineen Bridge |
| CC-L4240-001.00 | Ardagh East Bridge | CC-L4641-001.00 | Ballingurteen Bridge | CC-L5031-001.00 | Garrison Bridge |
| CC-L4244-001.00 | Froe East Bridge | CC-L4641-002.00 | Ballinvard Bridge | CC-L5032-001.00 | Glennamucklagh Lower Bridge |
| CC-L4244-002.00 | Froe West Bridge | CC-L4641-003.00 | Kilmeen Bridge | CC-L5032-002.00 | Glennamucklagh Upper Bridge |
| CC-L4401-001.00 | Lissagriffin Bridge | CC-L4641-004.00 | Lyre Bridge | CC-L5034-001.00 | Glennamucklagh East Bridge |
| CC-L4402-001.00 | Goleen Causeway North Bridge | CC-L4642-001.00 | Derryvreen Bridge | CC-L5061-001.00 | Lismeelcunnin Bridge |
| CC-L4403-001.00 | Dunmanus Bridge | CC-L4701-001.00 | Ardnabroga Bridge | CC-L5062-001.00 | Knockduff Upper South Bridge |
| CC-L4410-001.00 | Ardmanagh Bridge | CC-L4704-001.00 | Clashadoo South Bridge | CC-L5072-001.00 | Knockatooan West Bridge |
| CC-L4413-001.00 | Rathruane Bridge | CC-L4704-002.00 | Clashadoo West Bridge | CC-L5077-001.00 | Foilogohig Bridge |
| CC-L4413-001.00 | Derreennaloame Bridge | CC-L4704-003.00 | Rossmore Bridge | CC-L5083-001.00 | Knocknanagh Commons Bridge |
| CC-L44134-001.00 | Coolcaha Bridge | CC-L4704-004.00 | Kealties Bridge | CC-L5088-001.00 | Doctor's Hill Bridge |
| CC-L44134-002.00 | Collagh More Bridge | CC-L4708-001.00 | Dromcooragh Bridge | CC-L5103-001.00 | Marybrook Bridge |
| CC-L44134-003.00 | Coolagh Bridge | CC-L4711-001.00 | Pookeen Bridge | CC-L5107-001.00 | Two Gneeves Bridge |
| CC-L4414-001.00 | Cooradarrigan Bridge | CC-L4717-001.00 | Cloonygorman Bridge | CC-L5111-001.00 | Barry's Bridge |
| CC-L4415-001.00 | Greenmount West Bridge | CC-L4717-002.00 | Mealagh Bridge | CC-L5114-001.00 | Ardine Bridge |
| CC-L4420-001.00 | Sleaveen Bridge | CC-L4719-001.00 | Donemark (Old) Bridge | CC-L5157-001.00 | Dromskarragh More Bridge |
| CC-L4421-001.00 | Coarliss Bridge | CC-L4719-002.00 | Donemark Bridge | CC-L5167-001.00 | Park Bridge |
| CC-L4429-001.00 | Glanakilleenagh Bridge | CC-L4723-001.00 | Old Snave Bridge | CC-L5170-001.00 | Shamrock Bridge |
| CC-L4437-001.00 | Knockeens Bridge | CC-L4724-001.00 | Coomhola Bridge | CC-L5170-002.00 | Ballydaly Rail Bridge |
| CC-L4604-001.00 | Greenville Bridge | CC-L4724-002.00 | Gowlane Upper Bridge | CC-L5171-001.00 | Ballydaly Bridge |
| CC-L4608-001.00 | Inchideraille Bridge | CC-L47242-001.00 | Derryduff Bridge | CC-L5173-001.00 | Coolanarney Bridge |
| CC-L4610-001.00 | Poulgorm Bridge | CC-L4725-001.00 | Dromore Bridge | CC-L5174-001.00 | Lyredaowen Bridge |
| CC-L4612-001.00 | Barrboy Bridge | CC-L4904-001.00 | Kealoge Bridge | CC-L5182-001.00 | Newquarter Bridge |
| CC-L4612-002.00 | Farnanes Bridge | CC-L4904-002.00 | Cloghane Bridge (Upper) | CC-L5188-001.00 | Shanaknock Bridge |
| CC-L4614-001.00 | Inch Bridge | CC-L4906-001.00 | Inchinteskin Bridge | CC-L5193-001.00 | Islandahill Bridge |
| CC-L4614-002.00 | Tonafora North Bridge | CC-L49080-001.00 | Eyeries Bridge | CC-L5210-001.00 | Elbow Lane Bridge |
| CC-L4614-003.00 | Dromleena Bridge | CC-L4910-002.00 | Barrees Bridge | CC-L5218-001.00 | Knockagallane Bridge |
| CC-L4617-001.00 | Cooryculline Bridge | CC-L4911-001.00 | Ardgroom Bridge | CC-L5218-002.00 | Knocknaloman Bridge |
| CC-L4620-001.00 | Dunmanway South Bridge | CC-L4913-001.00 | Kilmackowen Bridge | CC-L5224-001.00 | Adrivale Bridge |
| CC-L4622-001.00 | Shanagh Bridge | CC-L4913-002.00 | Kilmackowen South Bridge | CC-L5224-002.00 | Ballynatona Bridge |
| CC-L4624-001.00 | Geara Bridge | CC-L4916-001.00 | Foildarrig Bridge | CC-L5227-001.00 | Minsters Bridge |
| CC-L4624-002.00 | Blackwater Bridge | CC-L4922-001.00 | Derrycreeven Bridge | CC-L5231-001.00 | Clashatrake Bridge |
| CC-L4626-001.00 | Ballaghanure Bridge | CC-L4927-001.00 | Dromdour Bridge | CC-L5231-002.00 | Laharan Bridge |
| CC-L4626-002.00 | Aghnaloobaun Bridge | CC-L4927-002.00 | Dereenboy Lower Bridge | CC-L5231-003.00 | Aubane School Bridge |
| CC-L4630-001.00 | Derrymeeleen Bridge | CC-L4927-003.00 | Lickeen West Bridge | CC-L5238-001.00 | Donoure East Bridge |

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|---|---|
| CC-L5239-001.00 | Crinnaloo Bridge | CC-L5370-001.00 | Clashmorgan Bridge | CC-L5526-002.00 | Altamira Bridge 2 |
| CC-L5243-001.00 | Nadbeg Bridge | CC-L5374-001.00 | Athnalacka Bridge | CC-L5529-001.00 | Longford Bridge |
| CC-L52431-001.00 | Nadanuller More Bridge | CC-L5376-001.00 | Ballyboght Bridge | CC-L5530-001.00 | Ballynadrideen Bridge |
| CC-L52434-001.00 | Nadanuller Beg Bridge | CC-L5378-001.00 | Jordan's Bridge | CC-L5531-001.00 | Ardskeagh Bridge |
| CC-L5244-001.00 | Horsemount Bridge | CC-L5378-002.00 | Milford Bridge | CC-L5533-001.00 | Ballyhay Bridge |
| CC-L5245-001.00 | Finnanfield Bridge | CC-L5381-001.00 | Glynn Bridge | CC-L5534-001.00 | Bealaghanattin Bridge |
| CC-L5246-001.00 | Lackdotia Bridge | CC-L5382-001.00 | Athnaleenta Bridge | CC-L5535-001.00 | Newtown North Bridge |
| CC-L5252-001.00 | Father Murphy's Bridge | CC-L5382-002.00 | Ballyknockane Bridge | CC-L5536-001.00 | Castlewrixon South Bridge |
| CC-L52552-001.00 | Crowley's Bridge | CC-L5383-001.00 | Mourneabbey South Bridge | CC-L5542-001.00 | Spital Bridge |
| CC-L5258-001.00 | Grenville Bridge | CC-L5385-001.00 | Mourneabbey North Bridge | CC-L5543-001.00 | Bregoge Bridge |
| CC-L5258-002.00 | Glennacurracat Bridge | CC-L5385-002.00 | Ballynamona South Bridge | CC-L5545-001.00 | Bantigeen Bridge |
| CC-L5305-001.00 | Knockardsharriv Bridge | CC-L5387-001.00 | Greenhill Bridge | CC-L5545-002.00 | Streamhill East Bridge |
| CC-L5308-001.00 | Ballythomas Bridge | CC-L5389-001.00 | Island Bridge 1 | CC-L5545-003.00 | Streamhill Bridge |
| CC-L53081-001.00 | Gurteennacloona Bridge | CC-L5389-002.00 | Island Bridge 2 | CC-L5545-004.00 | Ballyshane Bridge |
| CC-L5310-001.00 | Rossnagussane Bridge | CC-L5389-003.00 | Tooreen North Upper Bridge | CC-L55511-001.00 | Ballinree Bridge |
| CC-L5314-001.00 | Gortnagross Bridge | CC-L5399-001.00 | Ballygriffin Bridge | CC-L5553-001.00 | Fluckane Bridge |
| CC-L5314-002.00 | Firville East Bridge | CC-L5399-002.00 | Knockbrack East Bridge | CC-L5554-001.00 | Skahanagh More Bridge |
| CC-L5320-001.00 | Parkadallane Bridge | CC-L5399-003.00 | Rahan Bridge | CC-L5565-001.00 | Ballyellis Bridge |
| CC-L5320-002.00 | Ballyviniter Bridge | CC-L5405-001.00 | Knockacullata Bridge | CC-L5565-002.00 | Cahermee Bridge |
| CC-L5320-003.00 | Ballyviniter Middle Bridge | CC-L54051-001.00 | Knockbrack West Bridge | CC-L5615-001.00 | Rathcormac Foot Bridge |
| CC-L5322-001.00 | Coolduragha Bridge | CC-L5406-001.00 | Ballygriffin East Bridge | CC-L5619-001.00 | O'Briens Bridge |
| CC-L5322-002.00 | Ballyviniter Upper Bridge | CC-L5411-002.00 | Dunlea's Bridge | CC-L5622-001.00 | Kilclooney Bridge |
| CC-L5327-001.00 | Kilcanway Bridge | CC-L5451-001.00 | Castlelishen Bridge | CC-L5622-002.00 | Graigue Bridge |
| CC-L5331-001.00 | Spaglen Bridge | CC-L54512-001.00 | Mullaheera Bridge | CC-L5628-001.00 | Labbamolloga bridge |
| CC-L5333-001.00 | Gortmore South Bridge | CC-L5465-001.00 | Catherine Bridge | CC-L5632-001.00 | Ballyarthur Bridge |
| CC-L5336-001.00 | Gurteenkreen Bridge | CC-L5466-001.00 | Kilberrihert Bridge | CC-L5636-001.00 | Furrow Bridge |
| CC-L5336-002.00 | Gortavoher Upper Bridge | CC-L5473-001.00 | Coon Bridge | CC-L5638-001.00 | Bealaboga Bridge |
| CC-L5336-004.00 | Gortroe North Bridge | CC-L5475-001.00 | Castlehill Bridge | CC-L5687-001.00 | Glannapreachaun Bridge |
| CC-L5336-005.00 | Lombardstown North Bridge | CC-L5478-001.00 | Aghnacallee Bridge | CC-L5711-001.00 | Ballybeg Bridge |
| CC-L5341-001.00 | Glannaharee Bridge | CC-L5515-001.00 | Lackeen Bridge | CC-L5753-001.00 | Pattersons Bridge |
| CC-L5341-002.00 | Monkey's Bridge | CC-L55152-001.00 | Carrigeen Bridge | CC-L5760-001.00 | Knockanannig Bridge |
| CC-L53411-001.00 | Glandine Bridge | CC-L5516-001.00 | Ballynageragh Bridge | CC-L5777-001.00 | Corbally Bridge |
| CC-L53411-002.00 | Cameen Stream | CC-L5516-002.00 | Scart Bridge | CC-L5780-001.00 | Condonstown Bridge |
| CC-L5345-001.00 | Lackavihoonig Bridge | CC-L5517-001.00 | Imogane Bridge | CC-L5782-001.00 | Maulane West Bridge |
| CC-L5346-001.00 | Glanminnane Bridge | CC-L5518-001.00 | Toberalisheen Bridge | CC-L5782-002.00 | Ballinaltig Bridge |
| CC-L5347-001.00 | Gneeves Bridge | CC-L5519-001.00 | Walshestown Bridge | CC-L5789-001.00 | Doctor's Bridge |
| CC-L5352-001.00 | Ballysimon Bridge | CC-L5520-001.00 | Bregoge Old Bridge | CC-L5797-001.00 | Aghern Bridge |
| CC-L5354-001.00 | Ballyboneill Bridge | CC-L5522-001.00 | Boherascrub East Bridge | CC-L5829-001.00 | Shanakill West Bridge |
| CC-L5365-001.00 | Atkinson's Bridge | CC-L5524-001.00 | Knockardbane Bridge | CC-L5846-001.00 | Mogeely Bridge |
| CC-L5367-001.00 | Carrigduff Bridge | CC-L5526-001.00 | Altamira Bridge 1 | CC-L59821-001.00 | Inches Bridge |

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|---|---|
| CC-L6002-001.00 | Ahageeragh Bridge | CC-L6770-001.00 | Athnangle Bridge | CC-L6989-001.00 | Ballynanelagh Bridge |
| CC-L6015-001.00 | Castlelands Bridge | CC-L6776-001.00 | Gowlane North Upper Bridge | CC-L6991-001.00 | Ballynagaul Bridge |
| CC-L6016-001.00 | Teadies Upper Bridge | CC-L67761-001.00 | Gowlane North Lower | CC-L6992-001.00 | Glenmore Bridge |
| CC-L6018-001.00 | Sranaviddoge Bridge | CC-L6778-001.00 | Meenahony Lower Bridge | CC-L6993-001.00 | Ballycurreen Bridge |
| CC-L6020-001.00 | Ahadine Bridge | CC-L6779-001.00 | Meenahony Upper Bridge | CC-L7019-001.00 | Ballymore Bridge |
| CC-L6039-001.00 | Tanyard Bridge | CC-L6781-001.00 | Knockyrourke Bridge | CC-L7203-001.00 | Killaminoge Bridge |
| CC-L6042-001.00 | Lisnagat Bridge | CC-L6784-001.00 | Coolmona Bridge | CC-L7229-001.00 | Farranamoy Bridge |
| CC-L6044-001.00 | Aghaphona Bridge | CC-L6785-001.00 | Buckleys Bridge | CC-L7285-001.00 | Knoppoge Bridge |
| CC-L6046-001.00 | Roughgrove Bridge | CC-L6791-001.00 | Ballyvodane West Bridge | CC-L7400-001.00 | Bardinche Bridge |
| CC-L6047-001.00 | Ballygarvey Bridge | CC-L6792-001.00 | Lackabane Bridge | CC-L7400-002.00 | Mahony's Bridge |
| CC-L6052-001.00 | Keyes Bridge | CC-L6793-001.00 | Firmount Bridge | CC-L7401-001.00 | Mileens Bridge |
| CC-L6063-001.00 | Meelon Bridge | CC-L6797-001.00 | Kilclogh North Bridge | CC-L7403-001.00 | Derrynasagart Bridge |
| CC-L6069-001.00 | Downdaniel Bridge | CC-L6798-001.00 | Gilgach Bridge | CC-L7406-001.00 | Gougane Barra Bridge |
| CC-L6069-002.00 | Bealaha Bridge | CC-L6802-001.00 | Carhue North Bridge | CC-L7406-002.00 | Keamcorravooly Bridge |
| CC-L6088-001.00 | Burrane Bridge | CC-L6804-001.00 | Ballymacoo Bridge | CC-L74063-001.00 | Gortafludig Bridge |
| CC-L6097-001.00 | Burren Bridge | CC-L6821-002.00 | Rockhill Bridge | CC-L7407-001.00 | Gurteenakilla Bridge |
| CC-L6102-001.00 | Bateman's Bridge | CC-L6821-003.00 | Pound Bridge | CC-L7407-002.00 | Coomdurcha Bridge |
| CC-L62001-001.00 | Bealaheen Bridge | CC-L6822-001.00 | Lyradane Bridge | CC-L7414-001.00 | Tir na Spideoga Bridge |
| CC-L6203-001.00 | Loughleigh Bridge | CC-L6829-001.00 | Ballyvodane East Bridge | CC-L7416-001.00 | CÚim a Mhinister Bridge |
| CC-L6207-001.00 | Ballynichane Bridge | CC-L6829-002.00 | Ballycraheen Bridge | CC-L7416-001.00 | Flats Bridge |
| CC-L62141-001.00 | Rooves Moore South Bridge | CC-L6830-002.00 | Garrycloyne Bridge | CC-L7418-001.00 | Kippagh West Bridge |
| CC-L6242-001.00 | Tuough Bridge | CC-L6832-001.00 | Ballymartin Bridge | CC-L7418-002.00 | Kippagh's Bridge |
| CC-L6242-002.00 | Rearour Bridge | CC-L6835-001.00 | Loughane Bridge | CC-L7422-001.00 | Curraghleigh Bridge |
| CC-L6243-001.00 | Curragheenbrein Bridge | CC-L68351-001.00 | Courtbrack North Bridge | CC-L7423-001.00 | Foherish Bridge |
| CC-L6255-001.00 | Tough Bridge | CC-L6842-001.00 | Sheep Bridge | CC-L7431-001.00 | Pol na Bro Bridge |
| CC-L6264-001.00 | Ballyhandle North Bridge | CC-L6950-001.00 | Badgers Hill Bridge | CC-L7433-001.00 | Aghacunna Bridge |
| CC-L6270-001.00 | Garranetwaterig Bridge | CC-L6951-001.00 | Quarry Bridge | CC-L7433-002.00 | Coolcaum Bridge |
| CC-L6273-001.00 | Belrose West Bridge | CC-L69511-001.00 | Glynn Bridge | CC-L74332-001.00 | Cloontycarty Bridge |
| CC-L6279-001.00 | Ballyhank Bridge | CC-L69571-001.00 | Lyrenamon Bridge | CC-L74333-001.00 | Lisboymore Bridge |
| CC-L6279-002.00 | Belrose East Bridge | CC-L69572-001.00 | Ford Bridge | CC-L74333-002.00 | Silvergrove Bridge |
| CC-L6281-001.00 | Ballymurphy South Bridge | CC-L6958-001.00 | Dromboy North Bridge | CC-L7457-001.00 | Teerbeg Bridge |
| CC-L6285-001.00 | Oldabbey West Bridge | CC-L6959-001.00 | Newline Bridge | CC-L7469-001.00 | River Road Bridge |
| CC-L6478-001.00 | Paddy's Bridge | CC-L6961-001.00 | Shanlyre Bridge | CC-L7472-001.00 | Clounavrick Bridge |
| CC-L6482-001.00 | Bealahareagh Bridge | CC-L6968-001.00 | Ardalaghta Bridge | CC-L7477-001.00 | Hanover Hall Bridge 1 |
| CC-L6485-001.00 | Ballea Bridge Upper | CC-L6973-001.00 | Templemichael Bridge | CC-L7477-002.00 | Hanover Hall Bridge 2 |
| CC-L6487-001.00 | Ballea Bridge Lower | CC-L6976-001.00 | Templeesque Bridge | CC-L7477-003.00 | Shanakiel Bridge |
| CC-L6506-001.00 | Dandy Bridge | CC-L6978-001.00 | Ballindeenisk Bridge | CC-L7478-001.00 | Morrisons Bridge |
| CC-L6737-001.00 | Ballinlining Bridge | CC-L6979-001.00 | Ballynabortagh Bridge | CC-L7478-002.00 | Morris' Bridge |
| CC-L6755-001.00 | Kilmartin Lower Bridge | CC-L6982-001.00 | Transtown North Bridge | CC-L7478-003.00 | Rusheen Bridge |
| CC-L6766-001.00 | BÚal na Marbh Bridge | CC-L6988-001.00 | Butlerstown Bridge | CC-L7600-001.00 | Glenaphuca Bridge |

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|---|---|
| CC-L7600-002.00 | Peafield Bridge | CC-L8057-001.00 | Ballinaffrin Bridge | CC-L8546-001.00 | Coolmountin East Bridge |
| CC-L7601-001.00 | Leadinton Bridge | CC-L8084-001.00 | Kilmaloda Bridge | CC-L8546-002.00 | Coolmountin West Bridge |
| CC-L7606-001.00 | Leadinton Bridge | CC-L8093-001.00 | Ring Bridge | CC-L8546-003.00 | Shanacrane Bridge |
| CC-L7615-001.00 | Ballynona Bridge | CC-L8103-001.00 | Lislevane Bridge | CC-L8547-001.00 | Tooreen Bridge |
| CC-L7615-002.00 | Bealaghanaffrin Bridge | CC-L8110-001.00 | Curaheen Bridge | CC-L8551-001.00 | Caha Bridge |
| CC-L7620-001.00 | Dungourney Bridge | CC-L8116-001.00 | Lisleetemple Bridge | CC-L8552-001.00 | Gortanure Bridge |
| CC-L7629-001.00 | Roxboro Upper Briidge | CC-L8214-001.00 | Inisbeg Bridge | CC-L8553-001.00 | Keelaraheen Bridge |
| CC-L7629-002.00 | Roxboro Lower Bridge | CC-L8218-001.00 | Lag Bridge | CC-L8555-001.00 | Coom Bridge |
| CC-L7691-001.00 | Dundullerick West Bridge | CC-L82330-001.00 | Glencurragh Bridge | CC-L8560-001.00 | Keenrath Bridge |
| CC-L7691-002.00 | Dundullerick Bridge | CC-L8244-001.00 | Bawnishal Cross Roads Bridge | CC-L8560-002.00 | Deerynacaheragh Bridge |
| CC-L7693-001.00 | Glendine Bridge | CC-L8265-001.00 | Forenaught Bridge | CC-L8573-001.00 | Tonafora South Bridge |
| CC-L7805-001.00 | Lyre Bridge | CC-L8276-001.00 | Toreen Bridge | CC-L8575-001.00 | Kilronane Bridge |
| CC-L7806-001.00 | Breeda Lower Bridge | CC-L8279-001.00 | Barnahulla South Bridge | CC-L8581-001.00 | Drinagh East Bridge |
| CC-L7809-001.00 | Breeda River | CC-L8281-001.00 | Cornishal Bridge | CC-L8585-002.00 | Lettergorman East Bridge |
| CC-L7812-001.00 | Meanoughter Bridge | CC-L8282-001.00 | Barnahulla North Bridge | CC-L8595-001.00 | Gearagh Bridge |
| CC-L7813-001.00 | Inch Bridge | CC-L8311-001.00 | Corran South Bridge | CC-L8596-001.00 | Liscubba Bridge |
| CC-L7824-001.00 | Ballyre East Bridge | CC-L8311-002.00 | Gortroe Bridge | CC-L8596-002.00 | Drohidachlair Bridge |
| CC-L7825-001.00 | Kilcounty Bridge | CC-L8321-001.00 | Inchanoon Bridge | CC-L8600-001.00 | Spa Water Bridge |
| CC-L7826-001.00 | Ballyre Bridge | CC-L8335-001.00 | Ballyvireen Bridge | CC-L8634-001.00 | Bealboy Bridge |
| CC-L7828-001.00 | Barnaviddane Bridge | CC-L8337-001.00 | Pier Road Bridge | CC-L8664-001.00 | Dromfeagh Bridge |
| CC-L78311-001.00 | Ballnamona Bridge | CC-L8340-001.00 | New Bridge | CC-L8667-001.00 | Ahakeera Bridge |
| CC-L7832-001.00 | Garryoughtra Bridge | CC-L8357-001.00 | Keamore Bridge | CC-L8669-001.00 | Anaharlick Bridge |
| CC-L7835-001.00 | Kilcraheen Bridge | CC-L8434-001.00 | Derreennatra Bridge | CC-L8720-001.00 | Clashadoo North Bridge |
| CC-L7838-001.00 | Ballycurraginny Bridge | CC-L8439-001.00 | Greenmount East Bridge | CC-L8737-001.00 | Caheragh Bridge |
| CC-L7841-001.00 | Acorn Bridge | CC-L8444-001.00 | Rosbrin Bridge | CC-L8748-001.00 | Sheehanes Bridge |
| CC-L7856-001.00 | Barters Bridge | CC-L8452-001.00 | Scrahanyleary Bridge | CC-L8749-001.00 | Gurteeniher Bridge |
| CC-L7881-001.00 | Shanavagoon Bridge | CC-L8459-001.00 | Lissaclarig West Bridge | CC-L8751-001.00 | Moyny Bridge |
| CC-L7882-001.00 | Ballybane Bridge | CC-L8460-001.00 | Cooravoley Bridge | CC-L8752-001.00 | Dromasta Bridge |
| CC-L7891-001.00 | Aghancoustha Bridge | CC-L8462-002.00 | Cooranuller Bridge | CC-L8756-001.00 | Trawlebane Lower Bridge |
| CC-L7895-001.00 | Two Mile Bridge | CC-L8462-003.00 | Prohoness Bridge | CC-L8756-002.00 | Gortnascreeny Bridge |
| CC-L80012-001.00 | Sarue Bridge | CC-L8464-001.00 | Garrane Bridge | CC-L8758-001.00 | Inchibeega North Bridge |
| CC-L80041-001.00 | Knocks Bridge | CC-L8475-001.00 | Roaringwater Bridge | CC-L8759-001.00 | Inchibeega South Bridge |
| CC-L8007-001.00 | Castleventry Bridge | CC-L8477-001.00 | Bealaclare Bridge | CC-L8760-001.00 | Derryishal Bridge |
| CC-L8010-002.00 | Ballyvackey bridge | CC-L8479-001.00 | Roaring Water Bridge | CC-L8761-001.00 | Trawlebane Bridge 1 |
| CC-L8018-001.00 | Temple Fachtna Bridge | CC-L8493-001.00 | Hare Island Bridge | CC-L8761-002.00 | Trawlebane Bridge |
| CC-L80221-001.00 | Knocknagappul Bridge | CC-L8515-001.00 | Moneygaff East Bridge | CC-L8765-001.00 | Castledonovan Bridge |
| CC-L8050-001.00 | Bealanacreagh Bridge | CC-L8542-002.00 | Tullagh Bridge | CC-L8765-002.00 | Leitra Upper Bridge |
| CC-L8054-001.00 | Ahamilla South Bridge | CC-L8542-003.00 | Coolmountin Bridge | CC-L8769-001.00 | Inchiclough Bridge |
| CC-L8055-001.00 | Tawnies Lower Bridge | CC-L8542-004.00 | Moneyreague North Bridge | CC-L8783-001.00 | Gowlane Lower Bridge |
| CC-L80561-001.00 | Ahamilla North Bridge | CC-L8542-005.00 | Moneyreague South Bridge | CC-L8786-001.00 | Coomhola Bridge |

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|---|---|
| CC-L8888-001.00 | Ballydonegan West Bridge | CC-L95791-005.00 | Inchamay South Bridge | CC-R522-010.00 | Labbavacun Bridge |
| CC-L8906-001.00 | Kilcaskan Bridge | CC-L95821-001.00 | Annagloor Bridge | CC-R522-010.01 | Labbavacun Bridge Approach |
| CC-L8910-001.00 | Knockroe Bridge | CC-L95842-001.00 | Carraig Bridge | CC-R548-001.00 | Derreendonee Bridge |
| CC-L89121-001.00 | Ballydonegan East Bridge | CC-L95943-001.00 | Cooridowny Bridge | CC-R571-001.00 | Kealineha Bridge |
| CC-L8916-001.00 | Aughabrack Bridge | CC-L97301-001.00 | Carrig Bridge | CC-R571-002.00 | Crumpane Bridge |
| CC-L89161-001.00 | Urhan Bridge | CC-LP3202-001.00 | Rathrore Bridge | CC-R571-003.00 | Barrees Bridge |
| CC-L8917-001.00 | Caherkeen Bridge | CC-LP3203-001.00 | Ballymartle Bridge | CC-R571-004.00 | Barrees North Bridge |
| CC-L8922-001.00 | Kilmackowen North Bridge | CC-LP3206-001.00 | Arlinstown Bridge | CC-R571-005.00 | Slieve Bridge |
| CC-L8923-001.00 | Kilmackowen East Bridge | CC-LP3207-001.00 | Cullen Bridge | CC-R571-006.00 | Gorteen Bridge |
| CC-L89293-001.00 | Bunskellig Bridge | CC-LP3209-001.00 | Gleann Na Geal South Bridge | CC-R572-001.00 | Glengarriff Bridge |
| CC-L8939-001.00 | Knockoura Bridge | CC-LP3209-002.00 | Gleann Na Geal North Bridge | CC-R572-002.00 | Magannagan Bridge |
| CC-L8940-001.00 | Drom South Bridge | CC-LP3211-001.00 | Ballyvrin Bridge | CC-R572-003.00 | Derryconnery Bridge |
| CC-L8940-002.00 | Curradonohoe Bridge | CC-LP3212-001.00 | Jagoe's Mills Bridge | CC-R572-004.00 | Trafrask Bridge |
| CC-L8945-001.00 | Rodeen Bridge | CC-LP3217-001.00 | The Cove Bridge | CC-R572-005.00 | Drumlave Bridge |
| CC-L8950-001.00 | Dereen Upper Bridge | CC-LP3227-001.00 | White Castle Bridge | CC-R572-007.00 | Reen Bridge |
| CC-L8960-001.00 | Inchintaglin Bridge | CC-LP7202-001.00 | Clougheenduane Bridge | CC-R572-008.00 | Curragh Castletownbere Bridge |
| CC-L89612-001.00 | Farranfada Bridge | CC-LS7222-001.00 | Sheep Dip Bridge | CC-R572-009.00 | Rossmackowen Bridge |
| CC-L8962-001.00 | Leitrim More Bridge | CC-LS7227-001.00 | Aghafantaugn Bridge | CC-R572-010.00 | Owgarriff Bridge |
| CC-L8962-002.00 | Curragh East Bridge | CC-LS7248-001.00 | Brown's Mills | CC-R572-011.00 | Rodeen Bridge |
| CC-L89643-001.00 | Crooha East Bridge | CC-LS7261-001.00 | Ballyhamsane Bridge | CC-R572-012.00 | Brandyhall Bridge |
| CC-L8968-001.00 | Dromgowlane Bridge | CC-LS7266-001.00 | Ballinaclashet Bridge | CC-R572-013.00 | Drom West Bridge |
| CC-L89682-001.00 | Curragh West Bridge | CC-LS7288-001.00 | Ballinscubbig Bridge | CC-R572-014.00 | Inchinagat Bridge |
| CC-L89732-001.00 | Coomarkane Bridge | CC-LS7314-001.00 | Post Office Bridge | CC-R572-015.00 | Gour Bridge |
| CC-L8974-001.00 | Rossnagrena Bridge | CC-N72-028.00 | Ballygriffin Rail Bridge | CC-R572-016.00 | Cloghane Bridge |
| CC-L8975-001.00 | Youngfield Bridge | CC-R513-001.00 | Gradoge Bridge | CC-R572-017.00 | Knockroe West Bridge |
| CC-L8978-001.00 | Gortroe Upper Bridge | CC-R513-002.00 | Ballyaghaderg Bridge | CC-R572-018.00 | Cloghfune Bridge |
| CC-L8979-001.00 | Gortroe Lower Bridge | CC-R515-001.00 | Fortlands Bridge | CC-R574-001.00 | Clashduff Bridge |
| CC-L8981-001.00 | Mill Little Bridge | CC-R515-002.00 | Fortlands West Bridge | CC-R574-002.00 | Inchintaglin (Healy Pass) Bridge |
| CC-L8982-002.00 | Mill Big Bridge | CC-R515-003.00 | Milford Bridge | CC-R575-000.70 | Killough East Bridge |
| CC-L9020-001.00 | Bearforest Lower Bridge | CC-R515-004.00 | Doony West Bridge | CC-R575-001.00 | Ballydonegan South Bridge |
| CC-L92001-001.00 | Ballynamona North Bridge | CC-R517-001.00 | Gortnaminna Bridge | CC-R575-002.00 | Ballydonegan Bridge |
| CC-L92001-002.00 | Lissard Bridge | CC-R517-002.00 | Ahaphuca Bridge | CC-R575-003.00 | Allihies North Bridge |
| CC-L92005-001.00 | Kilknockan Bridge | CC-R522-001.00 | Fortwilliam Bridge | CC-R575-004.00 | Caherkeen Bridge |
| CC-L95221-001.00 | Mountcorbett Bridge | CC-R522-002.00 | Prohust Bridge | CC-R575-005.00 | Urhin Bridge |
| CC-L95723-001.00 | Ballynakilla Bridge | CC-R522-003.00 | Cromoge Bridge | CC-R575-006.00 | Travara Bridge |
| CC-L95743-001.00 | Dromgarvan Bridge | CC-R522-004.00 | Aughrim Bridge | CC-R575-007.00 | Drehidawillaun Bridge |
| CC-L95791-001.00 | Glenaknockane Bridge | CC-R522-005.00 | Rockspring Holy Well Bridge | CC-R576-001.00 | Greenane Bridge |
| CC-L95791-002.00 | Glannaharee West Bridge | CC-R522-007.00 | Bregoge Railway X Bridge | CC-R576-002.00 | Curragh Bridge |
| CC-L95791-003.00 | Caheraveelane North Bridge | CC-R522-008.00 | Buttevant Old Bridge | CC-R576-003.00 | Ballydrohane Bridge |
| CC-L95791-004.00 | Caheraveelane South Bridge | CC-R522-009.00 | Oldcourt Bridge | CC-R576-004.00 | Park Bridge |

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|---|---|
| CC-R576-006.00 | Aldworth's Bridge | CC-R579-010.00 | Barrahaurin Bridge North. | CC-R582-013.00 | Courthouse Bridge |
| CC-R576-007.00 | Meens Bridge | CC-R579-010.20 | Barrahaurin Bridge | CC-R582-014.00 | Scrahan Bridge |
| CC-R576-008.00 | Meengorman South Bridge | CC-R579-011.00 | Glencam Bridge | CC-R582-015.00 | Glencollins Upper Bridge |
| CC-R576-009.00 | Meengorman Middle Bridge | CC-R579-012.00 | Knock River Bridge | CC-R583-001.00 | Tanyard Bridge |
| CC-R576-010.00 | Ballinatona Water Works Bridge | CC-R579-013.00 | Monanveel Bridge | CC-R583-002.00 | Drishane More Bridge |
| CC-R576-011.00 | Tooreennaguppoge South Bridge | CC-R579-014.00 | Nad Bridge | CC-R583-005.00 | Keale Bridge |
| CC-R576-012.00 | Tooreennaguppoge Middle Bridge | CC-R579-015.00 | Lacka South Bridge | CC-R583-006.00 | Garrane Bridge |
| CC-R576-013.00 | Tooreen Donnell Bridge | CC-R579-016.00 | Glen South Bridge | CC-R583-007.00 | Carver Underpass |
| CC-R576-014.00 | Meentinny East Bridge | CC-R579-017.00 | Fermoyle Bridge | CC-R583-008.00 | Dromskehy Bridge |
| CC-R576-015.00 | Cronin's Bridge | CC-R579-018.00 | Glenpike Bridge | CC-R584-001.00 | Toon Bridge 1 |
| CC-R576-016.00 | Glenacarney Bridge | CC-R579-021.00 | Ballymaquirk Bridge | CC-R584-002.00 | Toon Bridge 2 |
| CC-R576-017.00 | Breanagh Bridge | CC-R579-022.00 | Ballymaquirk Bridge North | CC-R584-003.00 | Kilbarry School Bridge |
| CC-R577-001.00 | Kingwilliamstown Bridge | CC-R579-023.00 | Paal East Bridge | CC-R584-004.00 | Inchigeelagh Bridge |
| CC-R577-002.00 | Glencollins Lower Bridge | CC-R579-024.00 | Kanturk Castle Br | CC-R584-005.00 | Graigue Bridge |
| CC-R577-003.00 | Kishkeam Bridge | CC-R579-025.00 | Kanturk Bridge | CC-R584-006.00 | Carrahy Br |
| CC-R577-003.10 | Kiskeam Lower Farm Underpass | CC-R579-026.00 | Curragh (Ed Kanturk) Bridge | CC-R584-007.00 | Kilmore Bridge |
| CC-R577-004.00 | Knockeenacurrig West Bridge | CC-R579-027.00 | Coolageela Br | CC-R584-008.00 | Ballingeary Bridge |
| CC-R577-005.00 | Knockeenacurrig East Br | CC-R579-028.00 | Kilknockane Bridge | CC-R584-009.00 | Inchinossig Bridge |
| CC-R577-006.00 | Maul Bridge | CC-R579-029.00 | Gortnascregga Bridge | CC-R584-010.00 | Tooreenduff Bridge |
| CC-R578-001.00 | Clamper Bridge | CC-R579-030.00 | Raheen Bridge Flood Relief | CC-R584-011.00 | Inchi More Bridge |
| CC-R578-002.00 | Glentanedowney Bridge | CC-R579-031.00 | Raheen Bridge | CC-R584-013.00 | Carriganass Castle |
| CC-R578-003.00 | Clashykinleen Bridge | CC-R579-032.00 | Raheen Bridge North | CC-R584-014.00 | Inchigearagh Bridge |
| CC-R578-004.00 | Ballyduane Bridge | CC-R579-033.00 | Cahernagh Bridge | CC-R584-015.00 | Lisheens Bridge |
| CC-R578-005.00 | Mountkeeffe Bridge | CC-R580-001.00 | Ballyhest Bridge | CC-R585-001.00 | Castlemore Bridge |
| CC-R578-006.00 | Barleyhill Bridge | CC-R580-002.00 | Sal's Bridge | CC-R585-002.00 | Garranenamuddagh Bridge |
| CC-R578-007.00 | West Toorard Bridge | CC-R580-003.00 | Glasheenytara Bridge | CC-R585-003.00 | Poularick Bridge |
| CC-R578-008.00 | East Toorard Bridge | CC-R580-004.00 | Lisgriffin Bridge | CC-R585-004.00 | Shanacashel Bridge |
| CC-R578-009.00 | Knockilly Bridge | CC-R580-005.00 | Annagorp Bridge | CC-R585-005.00 | Lisheenleigh Bridge |
| CC-R578-010.00 | Allow Bridge | CC-R581-001.00 | Doneraile Bridge | CC-R585-006.00 | Shanlaragh East Pipe Culvert |
| CC-R578-011.00 | Freemount Bridge | CC-R582-001.00 | Carriganimmy Bridge | CC-R585-007.00 | Shanlaragh West Pipe Culvert |
| CC-R578-012.00 | Cromoge Bridge | CC-R582-002.00 | Keel Bridge | CC-R585-009.00 | Inchincurka Bridge |
| CC-R578-013.00 | Dromina Bridge | CC-R582-003.00 | Kilmeedy Bridge | CC-R585-010.00 | Poulnaberry Bridge |
| CC-R579-001.00 | Garde's Bridge | CC-R582-004.00 | Dromascoolane Bridge | CC-R585-011.00 | Togher Bridge |
| CC-R579-002.00 | Vicarstown River Bridge | CC-R582-005.00 | Inchileigh Bridge | CC-R585-012.00 | Derragh Bridge |
| CC-R579-003.00 | Ballyshoneen Bridge | CC-R582-007.00 | Claraghatlea North Bridge | CC-R585-013.00 | Glanycarney Bridge |
| CC-R579-005.00 | Ballycunningham Bridge | CC-R582-008.00 | Ferm Bridge | CC-R585-014.00 | Carrigacorra Bridge |
| CC-R579-006.00 | Ballykerwick Bridge | CC-R582-009.00 | McCarthy's Bridge | CC-R585-015.00 | Cousane East Bridge |
| CC-R579-007.00 | Brew's Bridge | CC-R582-010.00 | Crooked Bridge | CC-R585-016.00 | Cousane Middle Bridge |
| CC-R579-008.00 | Barrahaurin Bridge East | CC-R582-011.00 | Inchibeg Bridge | CC-R585-017.00 | Cousane West Bridge |
| CC-R579-009.00 | Barrahaurin Bridge West. | CC-R582-012.00 | Novahal Bridge | CC-R585-018.00 | Maughanaclea East Bridge |

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|---|---|
| CC-R585-019.00 | Maughanaclea Middle Bridge | CC-R589-001.00 | Priest's Bridge | CC-R600-016.00 | Garranefeen Strand Culverts |
| CC-R585-020.00 | Maughanaclea West Bridge | CC-R589-002.00 | Coolatooder Bridge | CC-R600-017.00 | Burren Bridge |
| CC-R585-021.00 | Kealkill Bridge | CC-R589-003.00 | Dissused Railway Bridge Killeady | CC-R600-018.00 | Church Bridge |
| CC-R586-001.00 | Bandon Bridge | CC-R589-004.00 | Killeady Bridge | CC-R601-001.00 | Abbey Bridge Timoleague |
| CC-R586-003.00 | Mawbeg Bridge | CC-R589-005.00 | Crossbarry Bridge | CC-R601-002.00 | Abbey Bridge Timoleague |
| CC-R586-004.00 | Palaceanne Bridge | CC-R589-006.00 | Brinny Bridge | CC-R602-001.00 | Hayes Bridge |
| CC-R586-005.00 | Castlelands Bridge | CC-R590-002.00 | Finnis Bridge | CC-R603-001.00 | Kilbrittan Bridge |
| CC-R586-006.00 | Blackwater (Water Br) Bridge | CC-R590-003.00 | Scarthamuck Bridge | CC-R603-002.00 | Barleyfield Bridge |
| CC-R586-007.00 | Idle Bridge | CC-R590-004.00 | Bellmount Lower Bridge | CC-R603-003.00 | Baltinakin Bridge |
| CC-R586-008.00 | Nedinagh Bridge | CC-R591-000.04 | Goleen Bridge 2 | CC-R603-004.00 | Maulmane Bridge |
| CC-R586-009.00 | Ballyhalwick Cattle Underpass | CC-R593-001.00 | Gortnaclohy Bridge | CC-R604-002.00 | Garretstown Bridge |
| CC-R586-010.00 | The Long Bridge | CC-R593-002.00 | Lurriga (South) Bridge | CC-R605-001.00 | Millwater Cross Roads Bridge |
| CC-R586-012.00 | Drimoleague Bridge | CC-R593-003.00 | Lurriga (North) Bridge | CC-R605-002.00 | Ballythomas East Bridge |
| CC-R586-013.00 | Garranes South Bridge | CC-R593-004.00 | Bunalun Bridge | CC-R605-003.00 | Knocksmall Bridge |
| CC-R586-014.00 | Ilen Bridge | CC-R593-007.00 | Maulnaskeha Bridge | CC-R605-004.00 | Coolmoreen Bridge |
| CC-R586-015.00 | Inchingerig Bridge | CC-R593-009.00 | Garranes Bridge | CC-R605-005.00 | Farnahoe Bridge |
| CC-R586-016.00 | Gortnascreeny Bridge | CC-R594-001.00 | Derreeny Bridge | CC-R606-001.00 | Gully Bridge |
| CC-R586-017.00 | Aghaville Bridge | CC-R594-003.00 | Madore Bridge | CC-R606-002.00 | Tisaxon More Bridge |
| CC-R586-018.00 | Cullomane East Bridge | CC-R594-005.00 | Cooradowny Bridge | CC-R607-001.00 | Ballynalouhy Bridge |
| CC-R586-019.00 | Scart Bridge | CC-R594-006.00 | Aghaville Bridge | CC-R607-002.00 | Ballintober Bridge |
| CC-R586-020.00 | Keilnascarta Bridge | CC-R597-001.00 | Rowry Bridge | CC-R607-003.00 | Garravesoge Bridge |
| CC-R587-001.00 | Dromcarra Bridge | CC-R598-001.00 | Owenahincha Bridge | CC-R610-001.00 | Rochestown Bridge |
| CC-R587-002.00 | Cooldaniel Bridge | CC-R599-002.00 | Kealrootha Bridge | CC-R610-002.00 | Sand Quay Bridge |
| CC-R587-003.00 | Cooldorrogha Bridge | CC-R599-003.00 | Clasheenahielan Bridge | CC-R610-003.00 | Strawhall Bridge |
| CC-R587-004.00 | Dromleigh Bridge | CC-R599-004.00 | Knockane Bridge | CC-R610-004.00 | Rafeen Village Bridge |
| CC-R587-006.00 | Woods Cross Bridge | CC-R599-005.00 | Knockane Lower Bridge | CC-R611-001.00 | Cooleens Bridge |
| CC-R587-007.00 | Ardcahan Bridge | CC-R599-006.00 | Kildee Bridge | CC-R611-002.00 | Ballyfeard Bridge |
| CC-R587-008.00 | Derreens Pipe Culvert | CC-R599-007.00 | Ballingurteen Bridge | CC-R611-003.00 | Ballinluig West Bridge |
| CC-R588-001.00 | Tawnies West Bridge | CC-R599-008.00 | Argideen Bridge | CC-R611-004.00 | Gore's Bridge |
| CC-R588-002.00 | Kilgarriff Bridge | CC-R599-009.00 | Aghamilla Bridge | CC-R612-002.00 | Kilnaglery Bridge |
| CC-R588-003.00 | Garranecore Bridge | CC-R599-010.00 | Ballyvackey Bridge | CC-R612-004.00 | Aghamarta Bridge |
| CC-R588-004.00 | Ballaghcummer Bridge | CC-R600-001.00 | Owenboy River Bridge | CC-R613-001.00 | CÚim Carraige Bridge |
| CC-R588-005.00 | Lyre Bridge | CC-R600-005.00 | Ballynacourty Bridge | CC-R613-002.00 | Glen Cross Roads Bridge |
| CC-R588-006.00 | Derrymeeleen Pipe Culvert | CC-R600-007.00 | Lybe Bridge | CC-R613-003.00 | Ballygarvan Bridge |
| CC-R588-008.00 | Overflow Bandon River | CC-R600-008.00 | Belgooly Bridge | CC-R613-004.00 | Five Mile Bridge |
| CC-R588-009.00 | Enniskean Bridge | CC-R600-011.00 | Archdeacon Duggan Bridge | CC-R613-005.00 | Ballinhassig Culvert |
| CC-R588-010.00 | Castlelands Bridge | CC-R600-012.00 | Ballymacredmond Bridge | CC-R614-001.00 | Templemichael Bridge |
| CC-R588-011.00 | Kilnacranagh West Bridge | CC-R600-013.00 | Ballinspittle Bridge East | CC-R614-002.00 | Lackendarragh South Bridge |
| CC-R588-012.00 | Clonomara Bridge | CC-R600-014.00 | Ballinspittle Bridge West | CC-R614-003.00 | Keam Bridge |
| CC-R588-016.00 | Coppeen Bridge | CC-R600-015.00 | Garranefeen Strand Bridge | CC-R614-004.00 | Lackendarragh Middle Bridge |

| Bridge ID No. | Bridge Name | Bridge ID No. | Bridge Name |
|---|---|---|---|
| CC-R614-005.00 | Glanreagh Bridge | CC-R626-008.00 | Ward's Bridge |
| CC-R614-006.00 | Behernagh Bridge | CC-R627-001.00 | Ballymartin Bridge |
| CC-R614-007.00 | Ahaclareen Bridge | CC-R627-002.00 | Rathfootera Bridge |
| CC-R616-001.00 | Annacarton Bridge | CC-R627-003.00 | Ballydonagh More Bridge |
| CC-R616-002.00 | Upper Glanmire Bridge | CC-R628-001.00 | Kilmacow Bridge |
| CC-R617-001.00 | Shean Bridge | CC-R628-002.00 | Curraglass Bridge |
| CC-R617-002.00 | Shean Bridge Flood Relief | CC-R628-003.00 | Curraheen Bridge |
| CC-R617-003.00 | Willison's Bridge | CC-R628-004.00 | Ballyneela Bridge |
| CC-R618-001.00 | Leemount Bridge | CC-R628-005.00 | Ballydaw Bridge |
| CC-R618-002.00 | Coolyduff Bridge | CC-R628-006.00 | Ballinterry Bridge |
| CC-R618-003.00 | Curraleigh Bridge | CC-R630-001.00 | Saleen Bridge |
| CC-R618-004.00 | Dripsey Bridge | CC-R632-001.00 | Carewswood Bridge |
| CC-R618-005.00 | Glashagarriff Bridge | CC-R632-002.00 | Knockglass Bridge |
| CC-R618-006.00 | New Bridge | CC-R633-001.00 | Bog Bridge |
| CC-R619-001.00 | Farnanes Bridge | CC-R633-003.00 | Gortavadda Bridge |
| CC-R619-004.00 | Colthurst's Bridge | CC-R633-004.00 | Lynch's Underpass |
| CC-R619-005.00 | Luskin's Bridge | CC-R634-002.00 | Foxhole Bridge |
| CC-R619-006.00 | Falvey's Bridge | CC-R637-005.00 | Curraghlickey Bridge |
| CC-R619-007.00 | Downey's Bridge | CC-R637-006.00 | Reavouler Bridge |
| CC-R619-008.00 | Manning's Cross Roads Bridge | CC-R637-007.00 | Carrigeeny Bridge |
| CC-R619-009.00 | Beenalaght Bridge | CC-R637-008.00 | Adrigool Bridge |
| CC-R619-010.00 | Cummeen Stream Bridge | CC-R638-001.00 | Quartertown Ind. Est.Bridge |
| CC-R619-011.00 | Beennamweel West Bridge | CC-R638-003.00 | Railway Bridge OBC 344 |
| CC-R619-012.00 | Casey's Bridge | CC-R639-001.00 | Glanmire Mill Bridge |
| CC-R619-013.00 | Clyda Bridge (Lower) | CC-R639-002.00 | Poulacurry South Bridge |
| CC-R619-014.00 | Quartertown Lower Bridge | CC-R639-004.00 | Sallybrook Bridge |
| CC-R620-001.00 | Clyda Bridge (Upper) | CC-R639-006.00 | Annacarton Bridge |
| CC-R620-003.00 | Mallow Bridge | CC-R639-007.00 | Condonstown Bridge |
| CC-R621-001.00 | Longfield's Bridge | CC-R639-008.00 | Blackstone Bridge |
| CC-R621-002.00 | Newberry Bridge | CC-R639-012.00 | Downing Bridge |
| CC-R622-001.00 | Cloghroe Bridge | CC-R665-001.00 | Brigown Bridge |
| CC-R624-001.00 | Slatty Bridge | CC-R665-002.00 | Gurteennaboul Bridge |
| CC-R624-002.00 | Belvelly Bridge | CC-R666-002.00 | Ballyderown Junction Bridge |
| CC-R626-000.50 | Carrigogna Bridge | CC-R666-003.00 | Coolalisheen Bridge |
| CC-R626-001.00 | Ballyedmond Bridge | CC-R666-004.00 | Ballynalacken Bridge |
| CC-R626-002.00 | Curragh Bridge | CC-R851-001.00 | Grange Road Bridge |
| CC-R626-004.00 | Lisgoold Bridge | CC-R855-001.00 | Rectory Old Carrigaline Rd Bridge |
| CC-R626-005.00 | Ballincurrig Bridge | CC-R880-001.00 | Tobins Bridge |
| CC-R626-006.00 | Rathcobane Bridge | | |
| CC-R626-007.00 | Ballinwillin Bridge | | |

## Appendix D

Bridge stock condition index, rehabilitation cost and net present value calculations

| Year | Planning time period | Strategy 1 | | | Strategy 2 | | | Strategy 3 | | | Strategy 4 | | | Strategy 5 | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | BSCI | Rehabilitation cost | NPV | BSCI | Rehabilitation cost | NPV | BSCI | Rehabilitation cost | NPV | BSCI | Rehabilitation cost | NPV | BSCI | Rehabilitation cost | NPV |
| 1 | **$T_0$** | **2.16** | **24,232,263** | **-** | **2.16** | **24,232,263** | **-519,048** | **2.16** | **24,232,263** | **-828,571** | **2.16** | **24,232,263** | **-1,904,762** | **2.16** | **24,232,263** | **-2,857,143** |
| 2 | | 2.22 | 24,446,163 | - | 2.14 | 24,446,163 | -494,331 | 2.11 | 23,460,661 | -789,116 | 1.98 | 22,212,908 | -1,814,059 | 1.89 | 21,203,230 | -2,721,088 |
| 3 | | 2.28 | 24,660,064 | - | 2.12 | 24,660,064 | -470,791 | 2.05 | 22,689,059 | -751,539 | 1.80 | 20,193,553 | -1,727,675 | 1.62 | 18,174,197 | -2,591,513 |
| 4 | | 2.33 | 24,873,964 | - | 2.10 | 24,873,964 | -448,373 | 2.00 | 21,917,457 | -715,751 | 1.62 | 18,174,197 | -1,645,405 | 1.35 | 15,145,164 | -2,468,107 |
| 5 | | 2.39 | 25,087,864 | - | 2.08 | 25,087,864 | -427,022 | 1.94 | 21,145,855 | -681,668 | 1.44 | 16,154,842 | -1,567,052 | 1.08 | 12,116,132 | -2,350,578 |
| 6 | | 2.45 | 25,301,764 | - | 2.07 | 25,301,764 | -406,687 | 1.89 | 20,374,252 | -649,207 | 1.26 | 14,135,487 | -1,492,431 | 0.81 | 9,087,099 | -2,238,646 |
| 7 | | 2.51 | 25,515,665 | - | 2.05 | 25,515,665 | -387,321 | 1.83 | 19,602,650 | -618,293 | 1.08 | 12,116,132 | -1,421,363 | 0.54 | 6,058,066 | -2,132,044 |
| 8 | | 2.57 | 25,729,565 | - | 2.03 | 25,729,565 | -368,877 | 1.78 | 18,831,048 | -588,850 | 0.90 | 10,096,776 | -1,353,679 | 0.27 | 3,029,033 | -2,030,518 |
| 9 | | 2.63 | 25,943,465 | - | 2.01 | 25,943,465 | -351,312 | 1.72 | 18,059,446 | -560,810 | 0.72 | 8,077,421 | -1,289,218 | **0.00** | **0** | - |
| 10 | | 2.68 | 26,157,366 | - | 1.99 | 26,157,366 | -334,583 | 1.67 | 17,287,844 | -534,105 | 0.54 | 6,058,066 | -1,227,827 | 0.06 | 714,176 | - |
| 11 | | 2.74 | 26,371,266 | - | 1.97 | 26,371,266 | -318,650 | 1.61 | 16,516,242 | -508,671 | 0.36 | 4,038,711 | -1,169,359 | 0.12 | 1,428,353 | - |
| 12 | | 2.80 | 26,585,166 | - | 1.95 | 26,585,166 | -303,476 | 1.56 | 15,744,640 | -484,449 | 0.18 | 2,019,355 | -1,113,675 | 0.18 | 2,142,529 | - |
| 13 | | 2.86 | 26,799,067 | - | 1.93 | 26,799,067 | -289,025 | 1.50 | 14,973,038 | -461,380 | **0.00** | **0** | - | 0.24 | 2,856,706 | - |
| 14 | | 2.92 | 27,012,967 | - | 1.92 | 27,012,967 | -275,262 | 1.45 | 14,201,435 | -439,409 | 0.06 | 714,176 | - | 0.29 | 3,570,882 | - |
| 15 | | 2.98 | 27,226,867 | - | 1.90 | 27,226,867 | -262,154 | 1.39 | 13,429,833 | -418,485 | 0.12 | 1,428,353 | - | 0.35 | 4,285,059 | - |
| 16 | | 3.03 | 27,440,767 | - | 1.88 | 27,440,767 | -249,671 | 1.34 | 12,658,231 | -398,557 | 0.18 | 2,142,529 | - | 0.41 | 4,999,235 | - |
| 17 | | 3.09 | 27,654,668 | - | 1.86 | 27,654,668 | -237,782 | 1.28 | 11,886,629 | -379,578 | 0.24 | 2,856,706 | - | 0.47 | 5,713,412 | - |
| **18** | **$T_1$** | **3.15** | **27,868,568** | **-** | **1.84** | **17,406,983** | **-226,459** | **1.23** | **11,115,027** | **-361,503** | **0.29** | **3,570,882** | **-** | **0.53** | **6,427,588** | **-** |
| 19 | | 3.20 | 28,074,441 | - | 1.83 | 17,168,950 | -215,675 | 1.11 | 10,003,524 | -344,289 | 0.35 | 4,285,059 | - | 0.59 | 7,141,765 | - |
| 20 | | 3.26 | 28,280,314 | - | 1.81 | 16,930,918 | -205,405 | 0.98 | 8,892,022 | -327,894 | 0.41 | 4,999,235 | - | 0.65 | 7,855,941 | - |
| 21 | | 3.31 | 28,486,187 | - | 1.80 | 16,692,885 | -195,624 | 0.86 | 7,780,519 | -312,280 | 0.47 | 5,713,412 | - | 0.71 | 8,570,118 | - |
| 22 | | 3.37 | 28,692,060 | - | 1.78 | 16,454,852 | -186,308 | 0.74 | 6,669,016 | -297,409 | 0.53 | 6,427,588 | - | 0.76 | 9,284,294 | - |
| 23 | | 3.42 | 28,897,934 | - | 1.77 | 16,216,819 | -177,436 | 0.62 | 5,557,514 | -283,247 | 0.59 | 7,141,765 | - | 0.82 | 9,998,471 | - |
| 24 | | 3.48 | 29,103,807 | - | 1.75 | 15,978,787 | -168,987 | 0.49 | 4,446,011 | -269,759 | 0.65 | 7,855,941 | - | 0.88 | 10,712,647 | - |
| 25 | | 3.53 | 29,309,680 | - | 1.74 | 15,740,754 | -160,940 | 0.37 | 3,334,508 | -256,913 | 0.71 | 8,570,118 | - | 0.94 | 11,426,824 | - |
| 26 | | 3.59 | 29,515,553 | - | 1.72 | 15,502,721 | -153,276 | 0.25 | 2,223,005 | -244,679 | 0.76 | 9,284,294 | - | **1.00** | **12,141,000** | -200,855 |
| 27 | | 3.64 | 29,721,426 | - | 1.71 | 15,264,689 | -145,977 | 0.12 | 1,111,503 | -233,028 | 0.82 | 9,998,471 | - | 0.94 | 11,426,824 | -191,291 |
| 28 | | 3.70 | 29,927,299 | - | 1.69 | 15,026,656 | -139,026 | **0.00** | **0** | - | 0.88 | 10,712,647 | - | 0.88 | 10,712,647 | -182,182 |
| 29 | | 3.75 | 30,133,172 | - | 1.68 | 14,788,623 | -132,406 | 0.06 | 714,176 | - | 0.94 | 11,426,824 | - | 0.82 | 9,998,471 | -173,506 |
| 30 | | 3.81 | 30,339,045 | - | 1.66 | 14,550,591 | -126,101 | 0.12 | 1,428,353 | - | **1.00** | **12,141,000** | -165,244 | 0.76 | 9,284,294 | -165,244 |
| 31 | | 3.86 | 30,544,919 | - | 1.65 | 14,312,558 | -120,096 | 0.18 | 2,142,529 | - | 0.94 | 11,426,824 | -157,375 | 0.71 | 8,570,118 | -157,375 |
| 32 | | 3.92 | 30,750,792 | - | 1.63 | 14,074,525 | -114,377 | 0.24 | 2,856,706 | - | 0.88 | 10,712,647 | -149,881 | 0.65 | 7,855,941 | -149,881 |
| 33 | | 3.97 | 30,956,665 | - | 1.62 | 13,836,492 | -108,931 | 0.29 | 3,570,882 | - | 0.82 | 9,998,471 | -142,744 | 0.59 | 7,141,765 | -142,744 |
| 34 | | 4.03 | 31,162,538 | - | 1.60 | 13,598,460 | -103,743 | 0.35 | 4,285,059 | - | 0.76 | 9,284,294 | -135,947 | 0.53 | 6,427,588 | -135,947 |
| **35** | **$T_2$** | **4.08** | **31,368,411** | **-** | **1.59** | **13,360,427** | **-98,803** | **0.41** | **4,999,235** | **-** | **0.71** | **8,570,118** | **-129,473** | **0.47** | **5,713,412** | **-129,473** |
| 36 | | 4.12 | 31,414,070 | - | 1.56 | 13,181,552 | -94,098 | 0.47 | 5,713,412 | - | 0.65 | 7,855,941 | -123,308 | 0.41 | 4,999,235 | -123,308 |
| 37 | | 4.16 | 31,459,729 | - | 1.52 | 13,002,677 | -89,617 | 0.53 | 6,427,588 | - | 0.59 | 7,141,765 | -117,436 | 0.35 | 4,285,059 | -117,436 |
| 38 | | 4.21 | 31,505,389 | - | 1.49 | 12,823,802 | -85,350 | 0.59 | 7,141,765 | - | 0.53 | 6,427,588 | -111,844 | 0.29 | 3,570,882 | -111,844 |
| 39 | | 4.25 | 31,551,048 | - | 1.45 | 12,644,927 | -81,286 | 0.65 | 7,855,941 | - | 0.47 | 5,713,412 | -106,518 | 0.24 | 2,856,706 | -106,518 |
| 40 | | 4.29 | 31,596,707 | - | 1.42 | 12,466,051 | -77,415 | 0.71 | 8,570,118 | - | 0.41 | 4,999,235 | -101,446 | 0.18 | 2,142,529 | -101,446 |
| 41 | | 4.33 | 31,642,366 | - | 1.38 | 12,287,176 | -73,728 | 0.76 | 9,284,294 | - | 0.35 | 4,285,059 | -96,615 | 0.12 | 1,428,353 | -96,615 |
| 42 | | 4.37 | 31,688,025 | - | 1.35 | 12,108,301 | -70,218 | 0.82 | 9,998,471 | - | 0.29 | 3,570,882 | -92,014 | 0.06 | 714,176 | -92,014 |
| 43 | | 4.41 | 31,733,684 | - | 1.31 | 11,929,426 | -66,874 | 0.88 | 10,712,647 | - | 0.24 | 2,856,706 | -87,633 | **0.00** | **0** | - |
| 44 | | 4.46 | 31,779,344 | - | 1.28 | 11,750,551 | -63,689 | 0.94 | 11,426,824 | - | 0.18 | 2,142,529 | -83,460 | 0.06 | 714,176 | - |
| 45 | | 4.50 | 31,825,003 | - | 1.24 | 11,571,676 | -60,657 | **1.00** | **12,141,000** | **-79,485** | 0.12 | 1,428,353 | -79,485 | 0.12 | 1,428,353 | - |
| 46 | | 4.54 | 31,870,662 | - | 1.21 | 11,392,801 | -57,768 | 0.94 | 11,426,824 | -75,700 | 0.06 | 714,176 | -75,700 | 0.18 | 2,142,529 | - |
| 47 | | 4.58 | 31,916,321 | - | 1.17 | 11,213,926 | -55,017 | 0.88 | 10,712,647 | -72,096 | **0.00** | **0** | - | 0.24 | 2,856,706 | - |
| 48 | | 4.62 | 31,961,980 | - | 1.14 | 11,035,050 | -52,397 | 0.82 | 9,998,471 | -68,662 | 0.06 | 714,176 | - | 0.29 | 3,570,882 | - |
| 49 | | 4.66 | 32,007,639 | - | 1.10 | 10,856,175 | -49,902 | 0.76 | 9,284,294 | -65,393 | 0.12 | 1,428,353 | - | 0.35 | 4,285,059 | - |
| 50 | | 4.71 | 32,053,299 | - | 1.07 | 10,677,300 | -47,526 | 0.71 | 8,570,118 | -62,279 | 0.18 | 2,142,529 | - | 0.41 | 4,999,235 | - |
| 51 | | 4.75 | 32,098,958 | - | 1.03 | 10,498,425 | -45,263 | 0.65 | 7,855,941 | -59,313 | 0.24 | 2,856,706 | - | 0.47 | 5,713,412 | - |
| **52** | **$T_3$** | **4.79** | **32,144,617** | **-** | **1.00** | **10,319,550** | **-43,108** | **0.59** | **7,141,765** | **-56,489** | **0.29** | **3,570,882** | **-** | **0.53** | **6,427,588** | **-** |
| 53 | | 4.80 | 32,150,549 | - | 0.97 | 10,035,095 | -41,055 | 0.53 | 6,427,588 | -53,799 | 0.35 | 4,285,059 | - | 0.59 | 7,141,765 | - |
| 54 | | 4.81 | 32,156,481 | - | 0.94 | 9,750,639 | -39,100 | 0.47 | 5,713,412 | -51,237 | 0.41 | 4,999,235 | - | 0.65 | 7,855,941 | - |
| 55 | | 4.82 | 32,162,413 | - | 0.91 | 9,466,184 | -37,238 | 0.41 | 4,999,235 | -48,797 | 0.47 | 5,713,412 | - | 0.71 | 8,570,118 | - |
| 56 | | 4.83 | 32,168,345 | - | 0.88 | 9,181,728 | -35,465 | 0.35 | 4,285,059 | -46,473 | 0.53 | 6,427,588 | - | 0.76 | 9,284,294 | - |
| 57 | | 4.84 | 32,174,277 | - | 0.85 | 8,897,273 | -33,776 | 0.29 | 3,570,882 | -44,260 | 0.59 | 7,141,765 | - | 0.82 | 9,998,471 | - |
| 58 | | 4.85 | 32,180,209 | - | 0.82 | 8,612,818 | -32,167 | 0.24 | 2,856,706 | -42,153 | 0.65 | 7,855,941 | - | 0.88 | 10,712,647 | - |
| 59 | | 4.86 | 32,186,141 | - | 0.79 | 8,328,362 | -30,636 | 0.18 | 2,142,529 | -40,145 | 0.71 | 8,570,118 | - | 0.94 | 11,426,824 | - |
| 60 | | 4.87 | 32,192,073 | - | 0.76 | 8,043,907 | -29,177 | 0.12 | 1,428,353 | -38,234 | 0.76 | 9,284,294 | - | **1.00** | **12,141,000** | -38,234 |
| 61 | | 4.89 | 32,198,006 | - | 0.74 | 7,759,451 | -27,787 | 0.06 | 714,176 | -36,413 | 0.82 | 9,998,471 | - | 0.94 | 11,426,824 | -36,413 |
| 62 | | 4.90 | 32,203,938 | - | 0.71 | 7,474,996 | -26,464 | **0.00** | **0** | - | 0.88 | 10,712,647 | - | 0.88 | 10,712,647 | -34,679 |
| 63 | | 4.91 | 32,209,870 | - | 0.68 | 7,190,540 | -25,204 | 0.06 | 714,176 | - | 0.94 | 11,426,824 | - | 0.82 | 9,998,471 | -33,028 |
| 64 | | 4.92 | 32,215,802 | - | 0.65 | 6,906,085 | -24,004 | 0.12 | 1,428,353 | - | **1.00** | **12,141,000** | -31,455 | 0.76 | 9,284,294 | -31,455 |
| 65 | | 4.93 | 32,221,734 | - | 0.62 | 6,621,630 | -22,861 | 0.18 | 2,142,529 | - | 0.94 | 11,426,824 | -29,957 | 0.71 | 8,570,118 | -29,957 |
| 66 | | 4.94 | 32,227,666 | - | 0.59 | 6,337,174 | -21,772 | 0.24 | 2,856,706 | - | 0.88 | 10,712,647 | -28,531 | 0.65 | 7,855,941 | -28,531 |
| 67 | | 4.95 | 32,233,598 | - | 0.56 | 6,052,719 | -20,735 | 0.29 | 3,570,882 | - | 0.82 | 9,998,471 | -27,172 | 0.59 | 7,141,765 | -27,172 |
| 68 | | 4.96 | 32,239,530 | - | 0.53 | 5,768,263 | -19,748 | 0.35 | 4,285,059 | - | 0.76 | 9,284,294 | -25,878 | 0.53 | 6,427,588 | -25,878 |
| **69** | **$T_4$** | **4.97** | **32,245,462** | **-** | **0.50** | **5,483,808** | **-18,808** | **0.41** | **4,999,235** | **-** | **0.71** | **8,570,118** | **-24,646** | **0.47** | **5,713,412** | **-24,646** |
| 70 | | 4.97 | 32,249,091 | - | 0.50 | 5,583,702 | -17,912 | 0.47 | 5,713,412 | - | 0.65 | 7,855,941 | -23,472 | 0.41 | 4,999,235 | -23,472 |
| 71 | | 4.97 | 32,252,720 | - | 0.51 | 5,683,595 | -17,059 | 0.53 | 6,427,588 | - | 0.59 | 7,141,765 | -22,355 | 0.35 | 4,285,059 | -22,355 |
| 72 | | 4.98 | 32,256,349 | - | 0.51 | 5,783,489 | -16,247 | 0.59 | 7,141,765 | - | 0.53 | 6,427,588 | -21,290 | 0.29 | 3,570,882 | -21,290 |
| 73 | | 4.98 | 32,259,978 | - | 0.52 | 5,883,383 | -15,473 | 0.65 | 7,855,941 | - | 0.47 | 5,713,412 | -20,276 | 0.24 | 2,856,706 | -20,276 |
| 74 | | 4.98 | 32,263,608 | - | 0.52 | 5,983,276 | -14,736 | 0.71 | 8,570,118 | - | 0.41 | 4,999,235 | -19,311 | 0.18 | 2,142,529 | -19,311 |
| 75 | | 4.98 | 32,267,237 | - | 0.53 | 6,083,170 | -14,035 | 0.76 | 9,284,294 | - | 0.35 | 4,285,059 | -18,391 | 0.12 | 1,428,353 | -18,391 |
| 76 | | 4.98 | 32,270,866 | - | 0.53 | 6,183,064 | -13,366 | 0.82 | 9,998,471 | - | 0.29 | 3,570,882 | -17,515 | 0.06 | 714,176 | -17,515 |
| 77 | | 4.98 | 32,274,495 | - | 0.54 | 6,282,957 | -12,730 | 0.88 | 10,712,647 | - | 0.24 | 2,856,706 | -16,681 | **0.00** | **0** | - |
| 78 | | 4.99 | 32,278,124 | - | 0.54 | 6,382,851 | -12,124 | 0.94 | 11,426,824 | - | 0.18 | 2,142,529 | -15,887 | 0.06 | 714,176 | - |
| 79 | | 4.99 | 32,281,753 | - | 0.55 | 6,482,744 | -11,546 | **1.00** | **12,141,000** | -15,130 | 0.12 | 1,428,353 | -15,130 | 0.12 | 1,428,353 | - |
| 80 | | 4.99 | 32,285,382 | - | 0.55 | 6,582,638 | -10,996 | 0.94 | 11,426,824 | -14,410 | 0.06 | 714,176 | -14,410 | 0.18 | 2,142,529 | - |
| 81 | | 4.99 | 32,289,011 | - | 0.56 | 6,682,532 | -10,473 | 0.88 | 10,712,647 | -13,724 | **0.00** | **0** | - | 0.24 | 2,856,706 | - |
| 82 | | 4.99 | 32,292,641 | - | 0.56 | 6,782,425 | -9,974 | 0.82 | 9,998,471 | -13,070 | 0.06 | 714,176 | - | 0.29 | 3,570,882 | - |
| 83 | | 4.99 | 32,296,270 | - | 0.57 | 6,882,319 | -9,499 | 0.76 | 9,284,294 | -12,448 | 0.12 | 1,428,353 | - | 0.35 | 4,285,059 | - |
| 84 | | 5.00 | 32,299,899 | - | 0.57 | 6,982,213 | -9,047 | 0.71 | 8,570,118 | -11,855 | 0.18 | 2,142,529 | - | 0.41 | 4,999,235 | - |
| 85 | | 5.00 | 32,303,528 | | 0.58 | 7,082,106 | -8,616 | 0.65 | 7,855,941 | -11,291 | 0.24 | 2,856,706 | - | 0.47 | 5,713,412 | - |
| **86** | **$T_5$** | **5.00** | **32,307,157** | | **0.58** | **7,182,000** | **-8,616** | **0.59** | **7,141,765** | **-10,753** | **0.29** | **3,570,882** | **-** | **0.53** | **6,427,588** | **-** |

# Appendix E

Survey questionnaire

**Questionnaire on the influencing factors of the prioritisation of bridge rehabilitation projects.**

Dear_________________,

I am undertaking research into the prioritisation of bridge rehabilitation projects as part of a Masters programme with Cork Institute of Technology and I would be obliged if you could spare me a few moments of your time in completing this Questionnaire.

Between 2012 and 2014, Cork County Council carried out Eirspan Principal Inspections on approximately 1,400 bridges on Regional and strategic Local Roads. Using the inspection data and through a survey of experienced practitioners and experts, I am endeavouring to establish the factors that influence the prioritisation of bridge rehabilitation projects.

I have indentified ten factors or variables that may influence the decision making process in the choice and prioritisation of rehabilitation projects. I would be grateful if you could rank in order of precedence the factors you believe should influence the choice and order of projects that should be undertaken i.e. if you believe *'Availability of alternative route'* to be the most important influencing factor, place an **'X'** in the column headed **'1'**, and so on through the ten factors listed in the Table below.

I am very grateful for your input into this research and the intention is that the findings of this study will provide Local Authorities with a decision making aid in the choice of bridge rehabilitation projects into the future.

| **Influencing factors** | **Ranking** | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **1** | **2** | **3** | **4** | **5** | **6** | **7** | **8** | **9** | **10** |
| Availability of alternative route | | | | | | | | | | |
| Average Annual Daily Traffic | | | | | | | | | | |
| Bridge material type Note 1 | | | | | | | | | | |
| Bridge type Note 2 | | | | | | | | | | |
| Hydraulic vulnerability Note3 | | | | | | | | | | |
| Number of spans | | | | | | | | | | |
| Overall structural condition Note 4 | | | | | | | | | | |
| Rehabilitation cost | | | | | | | | | | |
| Road classification Note 5 | | | | | | | | | | |
| Structural (non-scour) condition Note 6 | | | | | | | | | | |

Note 1:- for example: stone masonry, in situ reinforced concrete, etc.

Note 2:- for example: arch bridge, simple span bridge, etc.

Note 3:- hydraulic vulnerability is being considered as it has been established that scour is a major contributor to bridge damage. In this research, hydraulic vulnerability is being taken as the highest Eirspan condition rating of either the ‘abutments’ or ‘piers’ condition rating.

Note 4:- overall structure condition is being taken as the Eirspan rating for the entire structure.

Note 5:- road classification is being considered in terms of Regional, Local Primary, Local Secondary and Local Tertiary Roads.

Note 6:- structural (non-scour) condition is being taken as the highest Eirspan condition rating of any of the critical component ratings, excluding the ‘abutments’ or ‘piers’.

Yours Sincerely,

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Liam Dromey